Hall & Dole

A Study of a Direct Current

Automatic Motor Starter

Electrical Engineering

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A STUDY OF A DIRECT CURRENT AUTOMATIC MOTOR STARTER

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THESIS

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Lawrence Melville Hall and Leslie Abijah Dole

ENTITLED A Study of a Direct Current Automatic Motor Starter

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Electrical Engineering

F. G. Willson
Instructor in Charge

APPROVED: Ernst Berg

HEAD OF DEPARTMENT OF Electrical Engineering

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A STUDY OF A DIRECT CURRENT AUTOMATIC MOTOR STARTER.

I. INTRODUCTION.

It is proposed in this paper to study the starting characteristics of a 15 H.P., 220 volt, variable speed, interpole, direct current motor used with an automatic starter. The starter is known as the A.S.B.K. type, Automatic Motor Controller made by the Electric Controller and Manufacturing Company of Cleveland, Ohio.

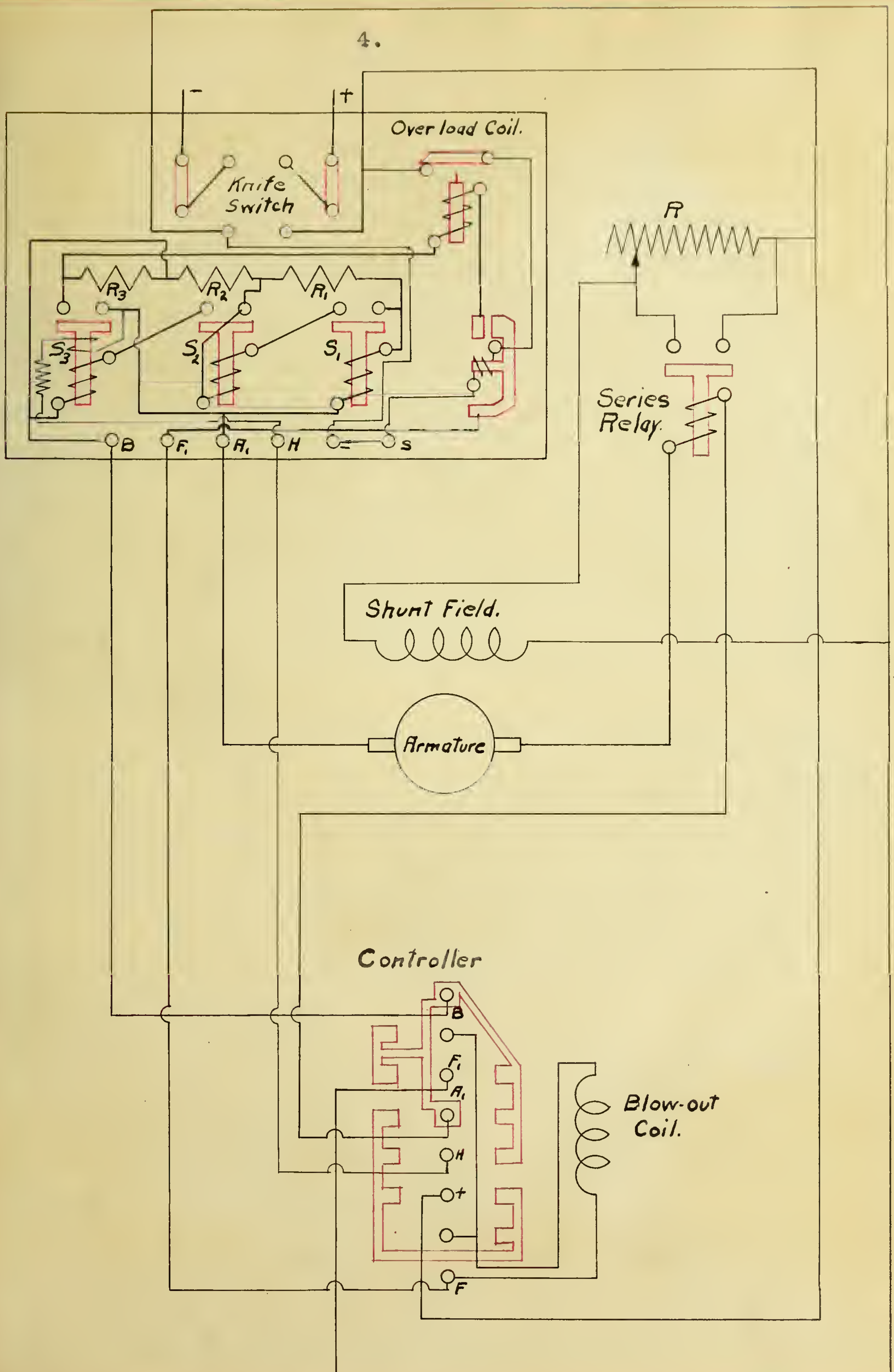
In order to have a basis of comparison, certain relations have been developed, theoretically, including certain experimental data, which have made these relations applicable to the particular case in hand. These curves have been obtained by the point by point method. In this connection, curves have been derived showing the effect of the variation of armature and field current upon the time of acceleration, thus making a combination of armature and field control.

Experimental curves of the armature current variation and also speed-time curves have been taken. The speed-time curves of the complete cycle of starting and braking have also been obtained, but no theoretical considerations have been made along this line. These curves simply show the effects of dynamic braking on the time of "deceleration" as compared with

the time required for the motor to come to a standstill by drifting.

A complete description of the starter connections and operation has been included, and also a description of the special type of magnetic switch and current relay.

Figure 1.



-
+
Over load Coil.
Knife Switch
R
R3
R2
R1
S3
S2
S1
Series Relay.
B
F1
A1
H
S
Shunt Field.
Armature
Controller
B
F1
A1
H
+
F
Blow-out Coil.

Figure 2.

II DESCRIPTION AND OPERATION OF STARTER.

The starting appartus used is of the automatic armature control type, which embodies the principle of the magnetic solenoid for the actuation of special type switches for cutting out the starting resistance. These switches operate automatically at a definite current value and always in the same order. As they will only operate when the starting current falls to a certain value, the armature is protected against excessive currents. The construction and operation of these switches, which act as relays and current limit devices will be described later.

Figure 1 is a photograph of the complete set-up, including the starter, and an inertia load, composed of a cast iron cylinder mounted on a shaft between bearings and belted to the motor, furnishing a resisting torque to acceleration.

In the following discussion reference is made to figure 2 which is a diagramatic sketch of the starter and controller connections.

When the line switch is closed, the shunt field is energized and the magnetic switch S closes, establishing a dynamic braking circuit through the controller, starting resistance, R_1, R_2, R_3, and the armature.

When the controller is thrown to the running position in either direction, current flows from the positive side of the line through the starting resistance R_1, R_2, R_3,

controller, armature, and operating coil of switch S_1, back to the negative side of the line and the motor starts. As the speed increases, the counter electromotive force increases, and the current decreases to such a value as will allow switch S_1 to close. When S_1 closes, section R_1 of the starting resistance is short-circuited, thus allowing more current to flow and the speed of the motor increases. This in turn causes the current to decrease to such a value as to permit S_2 to close, short-circuiting section R_2 of the resistance and the speed of the motor increases. In a similar manner S_3 closes, putting the armature directly across the line and the motor builds up to normal speed. When S_3 closes, the operating coils of S_1 and S_2 are "deenergized" and the shunt holding coil of S_3 is put across the line. This allows S_1 and S_2 to drop out and S_3 remains closed.

The starter is provided with an external field resistance R for speed control. Should an attempt be made to start the motor under heavy load and a weakened field, an excessive current will flow momentarily, but this will cause the series wound shunt field relay to close, short-circuiting the resistance R, and this will allow the motor to start with full field excitation and hence full starting torque. This field relay is an ordinary solenoid type switch. When the armature current reaches a given value, the plunger is pulled up and a copper disc short-circuits the resistance through a pair of

carbon brushes.

The controller is provided with means for dynamic braking, already mentioned. By dynamic braking is meant the retarding effect on an electric motor, when circuits are established which will cause the rotating motor to act as a generator, compelling the flow of current through an adjustable external resistance. When the controller is thrown from the running to the off position, the operating and shunt coils of switch S_3 are "deenergized", allowing S_3 to drop out. The armature is then short-circuited through the resistances R_1, R_2, R_3. As the current decreases, switches S_1, S_2, S_3, act the same as in starting, finally completely short-circuiting thearmature upon itself and the motor comes to rest.

The motor may be reversed from full speed in one direction to full speed in the opposite direction by throwing the controller from one side to the other. In this case the dynamic braking circuit is established and the motor stops, then automatically starts in the reverse direction. All the reversing connections are made in the controller.

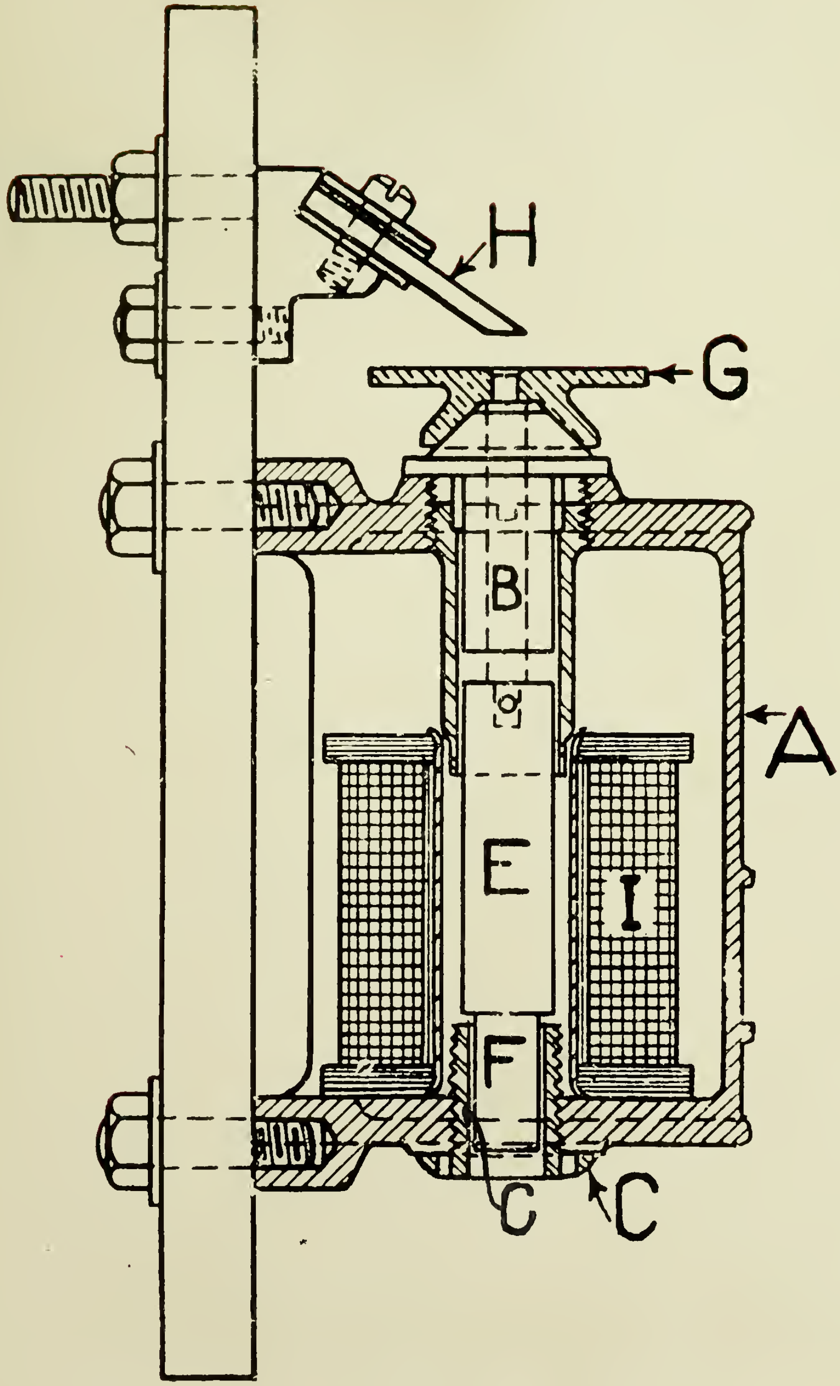


Figure 3.

III DESCRIPTION AND OPERATION OF AUTOMATIC SWITCHES.

The magnetic switches S_1, S_2, S_3, figure 2 act as a throttle or current limit relay. If a current below a predetermined critical value flows through the winding of the switch coil, the switch will close instantly, but for a value above this, the switch will remain open until the current falls to the closing value. The critical point may be adjusted at will so that the accelerating current taken by the motor may be varied.

Figure 3 is a cross-sectional view of the switch and reference is made to this figure in the following discussion.

The operating coil, I, is wound so that it can be put in series with the armature. It is wound on a brass tube within which a magnetic core, E, has a free vertical motion. On the upper end of E is mounted a brass stud, carrying a circular copper plate, which makes contact with the brushes, H, when the switch is closed. A stem, F, meets the body of the core, E, forming a square shoulder. This stem extends down into C which is a hollow adjustable plug of magnetic material. Enclosing and protecting the winding is an iron case, A. The upper end of this case carries a hollow plug, B, of magnetic material similar to plug C, but is not adjustable.

The action of the switch depends upon the magnetic reluctance of the stem, F, when in a saturated condition.

A current flowing in the coil, I, produces a flux which passes up through E into B and into the iron case, A, back through C into E. An upward pull on the plunger, E, is exerted by B and if the stem, F, is not in a saturated condition, the switch closes. If, however, the amount of flux is so great that F is saturated, the flux will divide inversely as the reluctance of the two paths and part will pass from C into the shoulder on E exerting a downward pull on the plunger which may or may not be sufficient to hold the switch open. This depends upon the degree of saturation of F and also upon the length of the air gap.

As the length of the air gap may be varied by screwing the plug, C, in or out, the value of current below, and at which, the switch will close can be varied. Hence a small air gap will give a low value of closing current and a long air gap a high value.

IV THEORY AND METHOD.

If the available torque, corresponding armature current, and mass accelerated are known, it is possible to obtain theoretical speed-time curves. In order to derive these curves the following assumptions must be made, first, constant acceleration, and second, constant torque during the interval considered. In this development the following nomenclature is used.

F = force in pounds.

M = mass in gee-pounds.

a = acceleration in feet per second^2.

K = radius of gyration in feet.

N = number of revolutions per minute.

ω = angular velocity in radians per second.

α = angular acceleration in radians per second^2.

r = radius of cylinder in feet.

T = available torque in pounds feet.

t = time in seconds.

I_a = armature current in amperes.

I_f = field current in amperes.

Starting with the fundamental equation

$$F = Ma$$

and assuming this force, F, to act at the radius of gyration, K, of the rotating body, then

$$F = MK\alpha$$

where

$$a = K\alpha$$

The radius of gyration of a homogenious cylinder revolving about the axis perpendicular to its faces is

$$K = r\sqrt{\tfrac{1}{2}}$$

Then $$F = Mr\alpha\sqrt{\tfrac{1}{2}}$$

If the torque in pounds feet is known and assuming this torque to act with a one foot lever arm, the torque is equal numerically to the force in pounds. Therefore, if it is desired to find the force which will have to act at the radius of gyration to produce the same effect, the torque must be divided by the radius of gyration in feet.

Then $$F = \frac{T}{K} = Mk\alpha$$

or $$\alpha = \frac{T}{MK^2}$$

Assuming constant acceleration

$$\alpha = \frac{w_2 - w_1}{t}$$

or $$t = \frac{w_2 - w_1}{\alpha}$$

but $$w = \frac{2\pi N}{60}$$

Substituting $$t = \frac{2\pi}{60} (N_2 - N_1)\frac{1}{\alpha}$$

or $$t = \frac{2\pi}{60} (N_2 - N_1) \frac{1}{\frac{T}{K^2 M}}$$

$$t = \frac{2\pi}{60} K^2 M \frac{N_2 - N_1}{T} = C \frac{N_2 - N_1}{T}$$

Now since the available torque, initial and final speed are known, the time required to accelerate the body from N_1 to N_2 may be determined.

Evaluation of Constant C.

Radius of cylinder = .822 ft.

Weight = 716 lb.

Mass = 22.24 gee - lbs.

Radius of gyration $K = R\sqrt{\frac{1}{2}} = .822 \times \sqrt{.5} = .581$ ft.

$$C = \frac{2\pi}{60} K^2 M = \frac{2\pi}{60} \overline{.581}^2 \times 22.24 = .7854$$

Then $t = .7854 \dfrac{N_2 - N_1}{T}$

Since it is the available torque corresponding to a given armature current and field current which is desired, this torque was taken by means of a prony brake on the shaft of the inertia load. Thefield current was held constant and the torque corresponding to different values of armature current from no load to full load was obtained. Then the field current was changed to another value and similar data taken. This gave the set of curves on page 18 between armature current and available torque with constant field current.

From these curves on page 18 it is possible to obtain a set of curves as shown on page 19 between field current and available torque with constant armature current.

On page 19 the no load field current-speed curve is drawn and from these curves it is possible to derive the theoretical speed-time curves for various conditions of field current and armature current. It is permissible to use the no load speed as the ultimate speed of the load because when there is no acceleration, no power is required to keep the mass in motion except that which has to supply the losses.

By selecting any armature current and the ultimate speed from the curves on page 19 the available torque can be obtained and the time required for acceleration computed from the equation, $t = C \frac{N_2 - N_1}{T}$. The power consumption in watt seconds may also be calculated.

The theoretical speed-time curves on pages 21,23,25,27 were obtained in this manner and show very clearly the effect of varying torque on the total time of acceleration. Curve (a) on page 21 was derived by assuming constant acceleration from start to ultimate speed of 800 R.P.M. and with constant torque throughout acceleration. In this case the change in speed is 800 R.P.M. and the armature current is assumed as constant at 40 amperes, also the field current corresponding to 800 R.P.M. is taken from the curve on page 19 as .57 amperes. Now from the torque-field current curves on page 19 the torque corresponding to 40 amperes armature current and .57 amperes field current is obtained and by substituting in the equation, $t = C \frac{N_2 - N_1}{T}$, the time, 9.675 seconds, is found. Curve (b) is obtained in a similar manner except that the speed is changed from 0-300 R.P.M. with full field current which gives a higher value of torque and hence a shorter time of acceleration. Then at 300 R.P.M. it is assumed that the field current is changed to .57 amperes and the body is allowed to accelerate from 300 R.P.M. to 800 R.P.M. with 40 amperes armature current and .57 amperes field current which

gives a certain value of torque as obtained from the torque-field current curves on page 19 . The curves (c) and (d) are obtained in similar manner, only the field is varied by different steps. In every case the field current is the value corresponding to the ultimate speed of the increment selected, that is, if the field were kept at this value the motor would come up to this speed. The curves on pages 23,25 are similar to those on page 21 except that different values of armature current were assumed.

The curves on page 27 were derived by assuming a variation of armature current. Curve (a) has constant field current throughout the time of acceleration and curve (b) has variable field current. However the general method of obtaining the curves is the same as for those described in the previous paragraph.

The curves on page 29 are very similar in character to those on page 27 except that the variations of armature current are different. Here the armature current is assumed to vary from 60 amperes to 40 amperes, then to 60 and then back to 40 and so on, while those on page 27 have a gradual decreasing value from 60 to 30 amperes.

Table I. Preliminary Data for
Armature current torque curves.

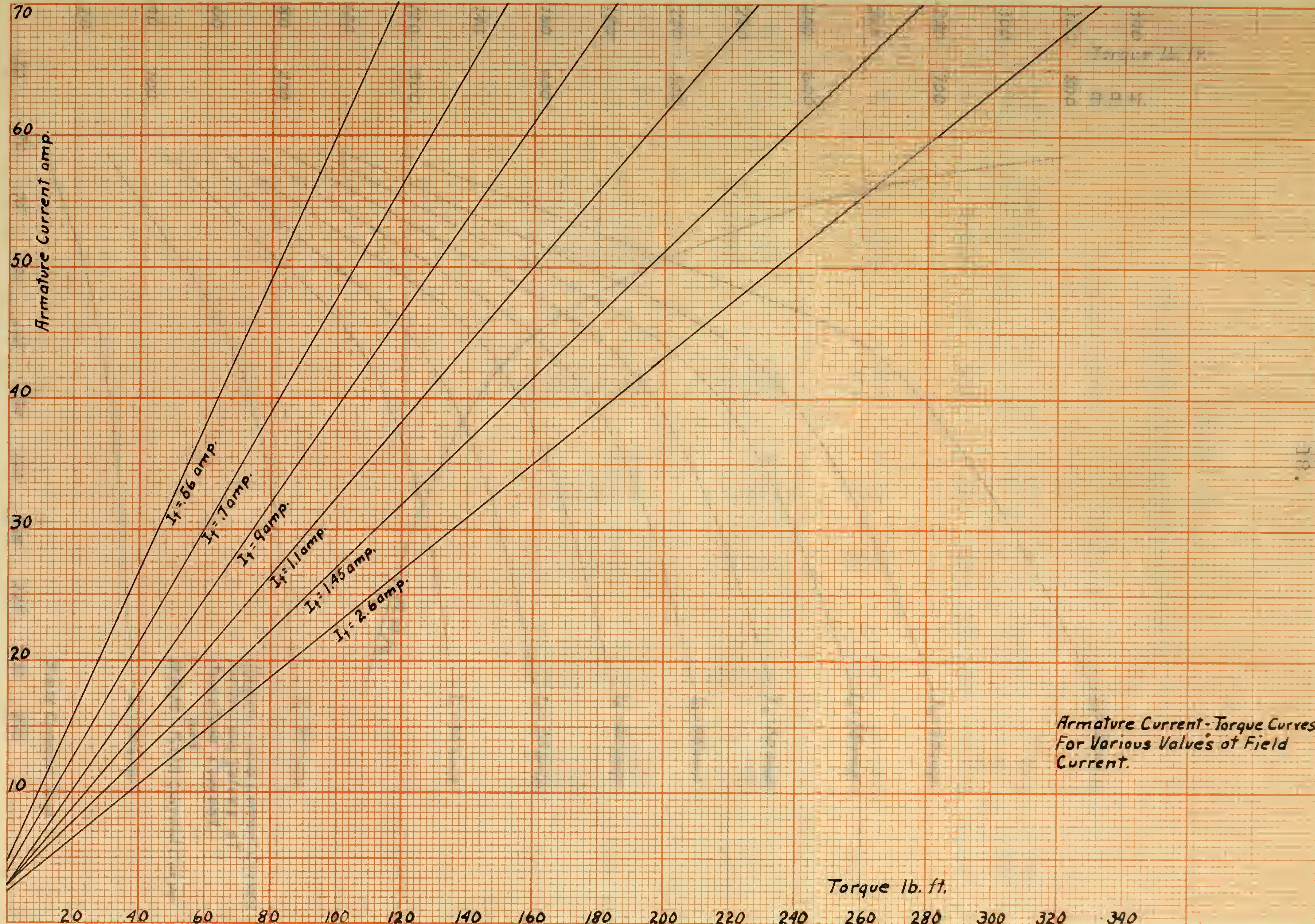
E = 220 volts -- constant. Brake constant = .531

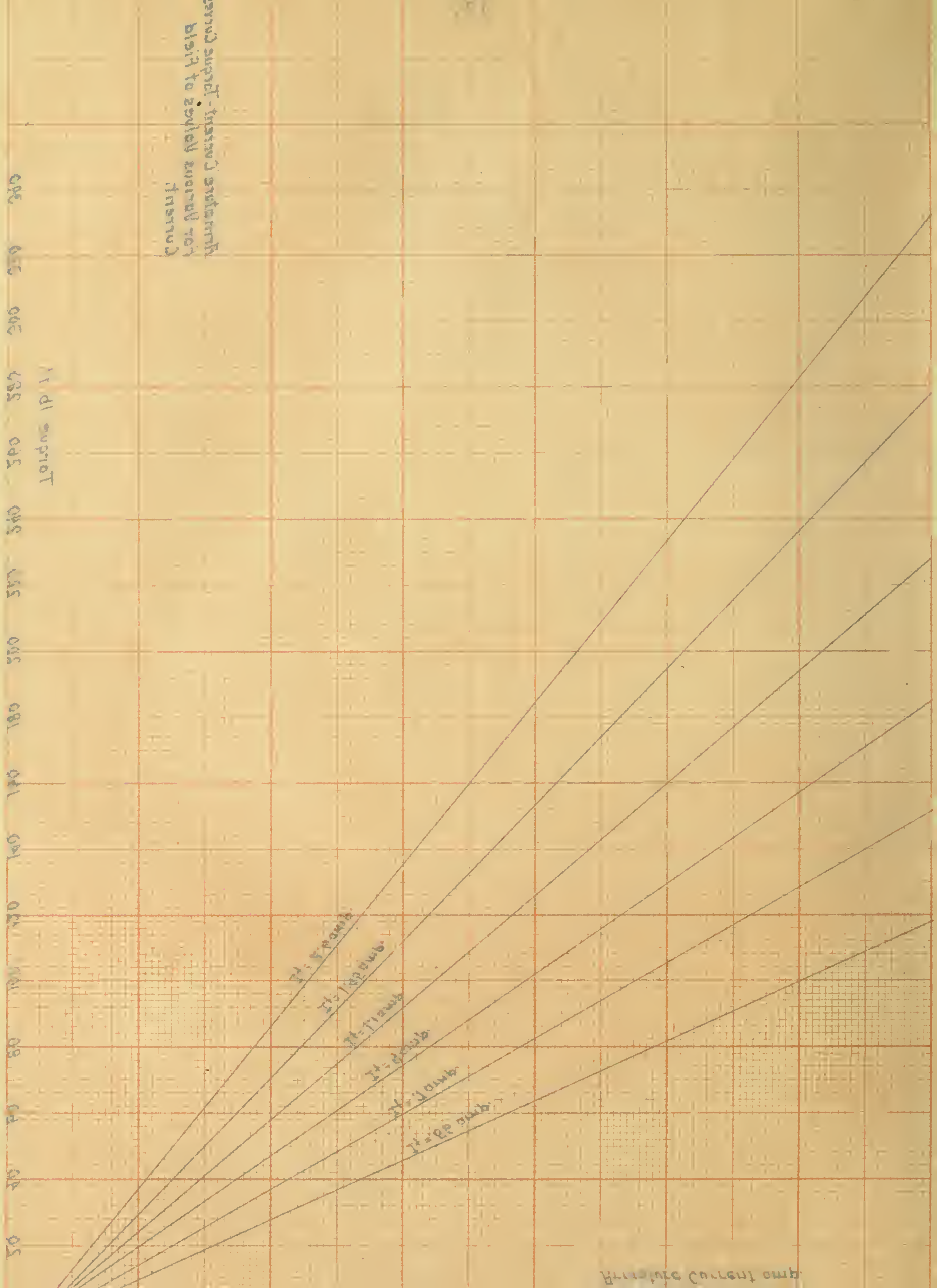
I_f	Lbs Brake	Lbs. Ft. Torque.	I_a
2.6	0	0	2.5
2.6	24.5	13	5.
2.6	70	37.2	10.
2.6	115	61.1	15.
2.6	165	87.5	20.
1.45	0	0	3
1.45	57	30.3	10
1.45	95	50.5	15
1.45	135	71.8	20
1.45	170	90.5	25
1.45	200	106.2	28
1.1	0	0	3
1.1	45	23.9	9.5
1.1	96	51.	15.
1.1	110	58.5	20.
1.1	136	72.3	25.
1.1	170	90.4	30.
1.1	205	109.	35.
.9	0	0	3
.9	55	29.2	12.5
.9	75	39.9	17.
.9	100	53.1	18.5
.9	120	63.85	20
.9	140	74.5	30
.9	165	87.75	35.
.9	205	109.	43.
.7	0	0	4
.7	27.5	14.6	10
.7	55	29.2	16
.7	80	42.5	22.5
.7	100	53.1	27
.7	130	69.1	35.
.7	155	82.5	40
.7	175	93.	45
.7	185	98.3	47.5
.7	235	124.9	55
.7	240	127.2	60

I_f	Lbs Brake	Lbs.Ft. Torque	I_a
.56	0	0	5
.56	35	18.6	14
.56	55	29.2	20
.56	80	42.5	29
.56	105	55.9	34

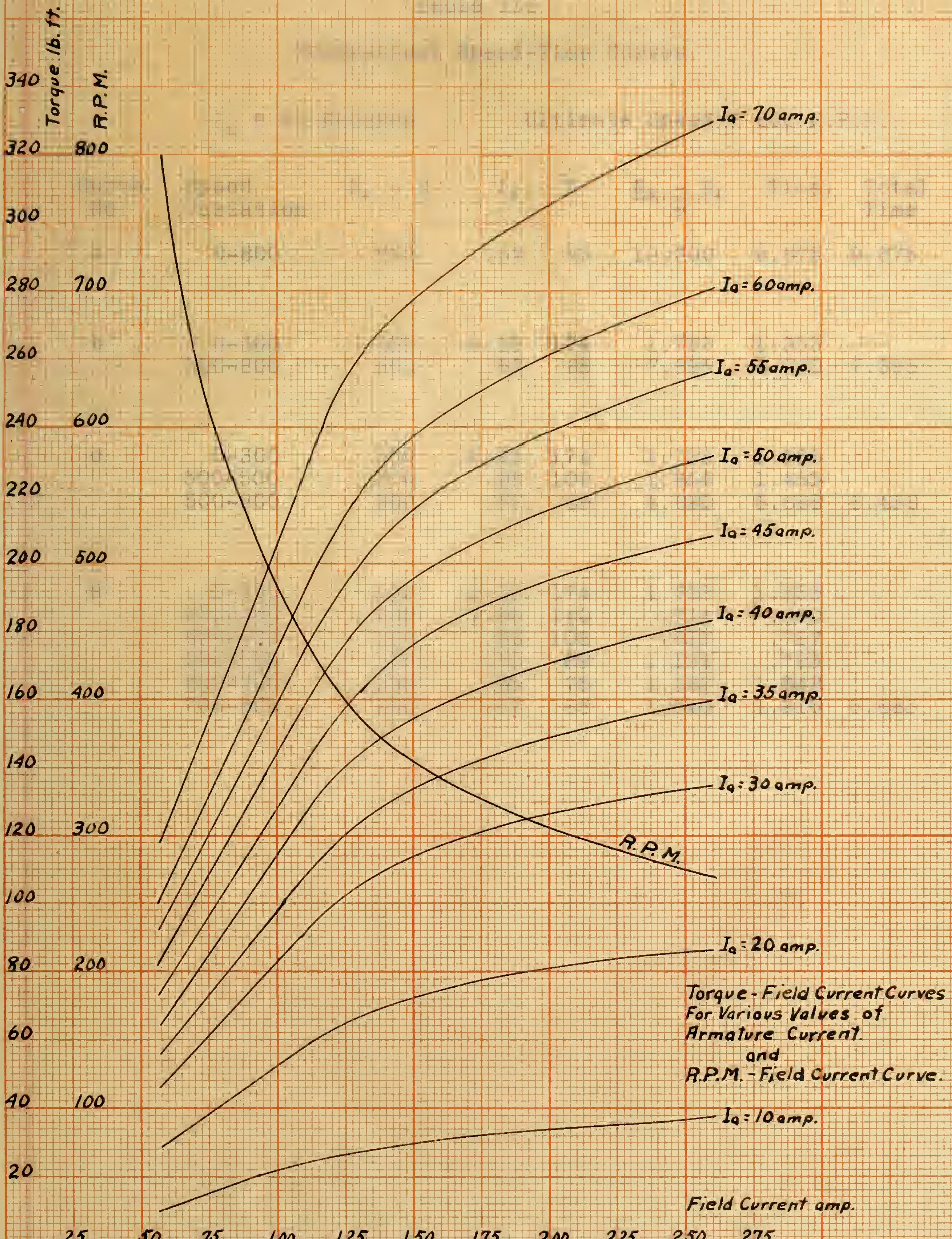
Table II. Data for Speed -- Field Current.

Field Current	R.P.M.
2.6	270
1.45	360
1.1	438
.9	530
.7	640
.56	811.5


Armature Current - Torque Curves For Various Values of Field Current.
Armature Current amp.
Torque lb. ft.
I_f = .66 amp.
I_f = .7 amp.
I_f = .9 amp.
I_f = 1.1 amp.
I_f = 1.45 amp.
I_f = 2.6 amp.
10
20
30
40
50
60
70
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340



Armature Current - Torque Curves for Various Values of Field Current
Torque lb ft
Armature Current amp


Torque lb. ft.
R.P.M.
340
320 800
300
280 700
260
240 600
220
200 500
180
160 400
140
120 300
100
80 200
60
40 100
20
.25 .50 .75 1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75
Field Current amp.
I_a = 70 amp.
I_a = 60 amp.
I_a = 55 amp.
I_a = 50 amp.
I_a = 45 amp.
I_a = 40 amp.
I_a = 35 amp.
I_a = 30 amp.
I_a = 20 amp.
I_a = 10 amp.
R.P.M.
Torque - Field Current Curves For Various Values of Armature Current and R.P.M. - Field Current Curve.

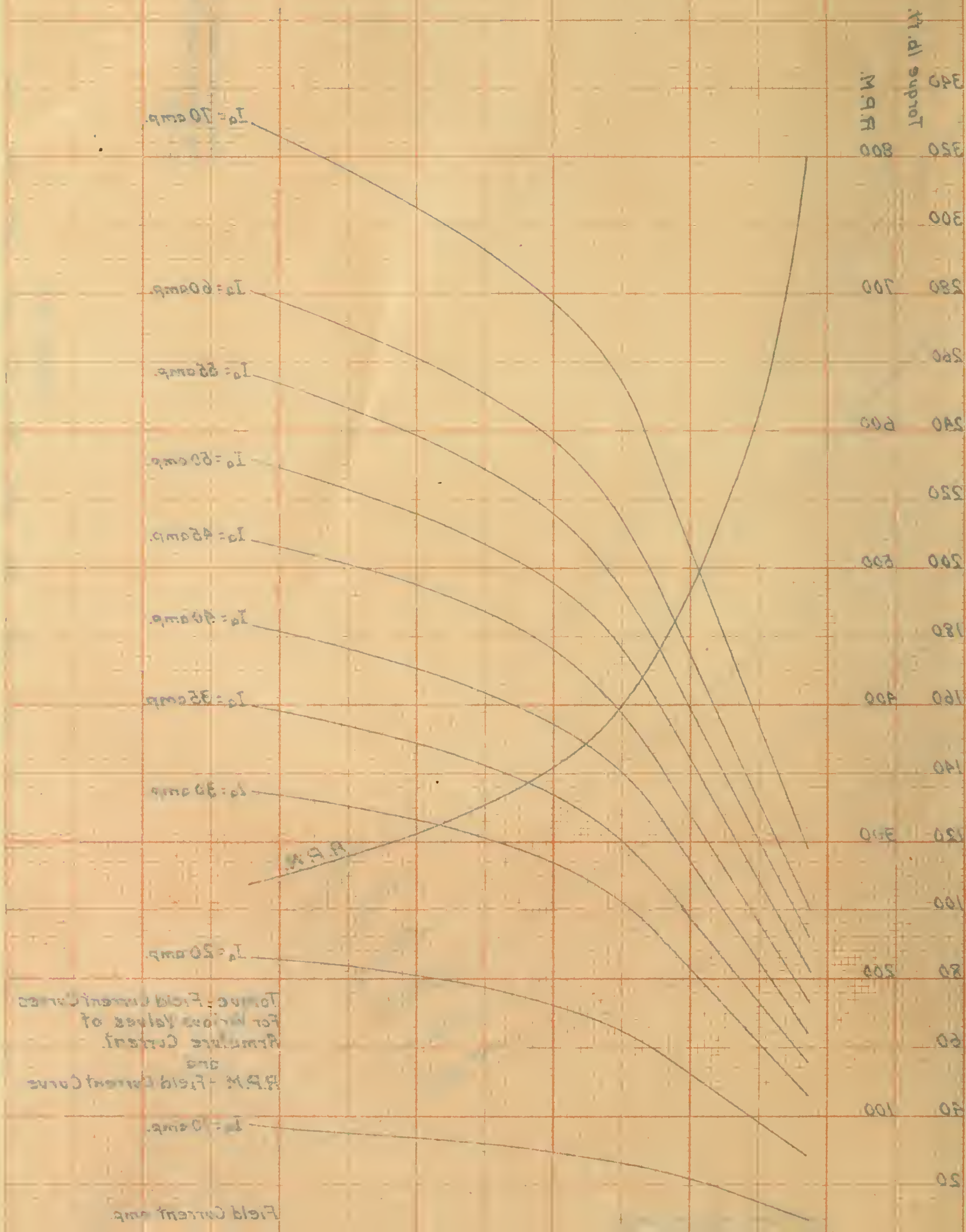
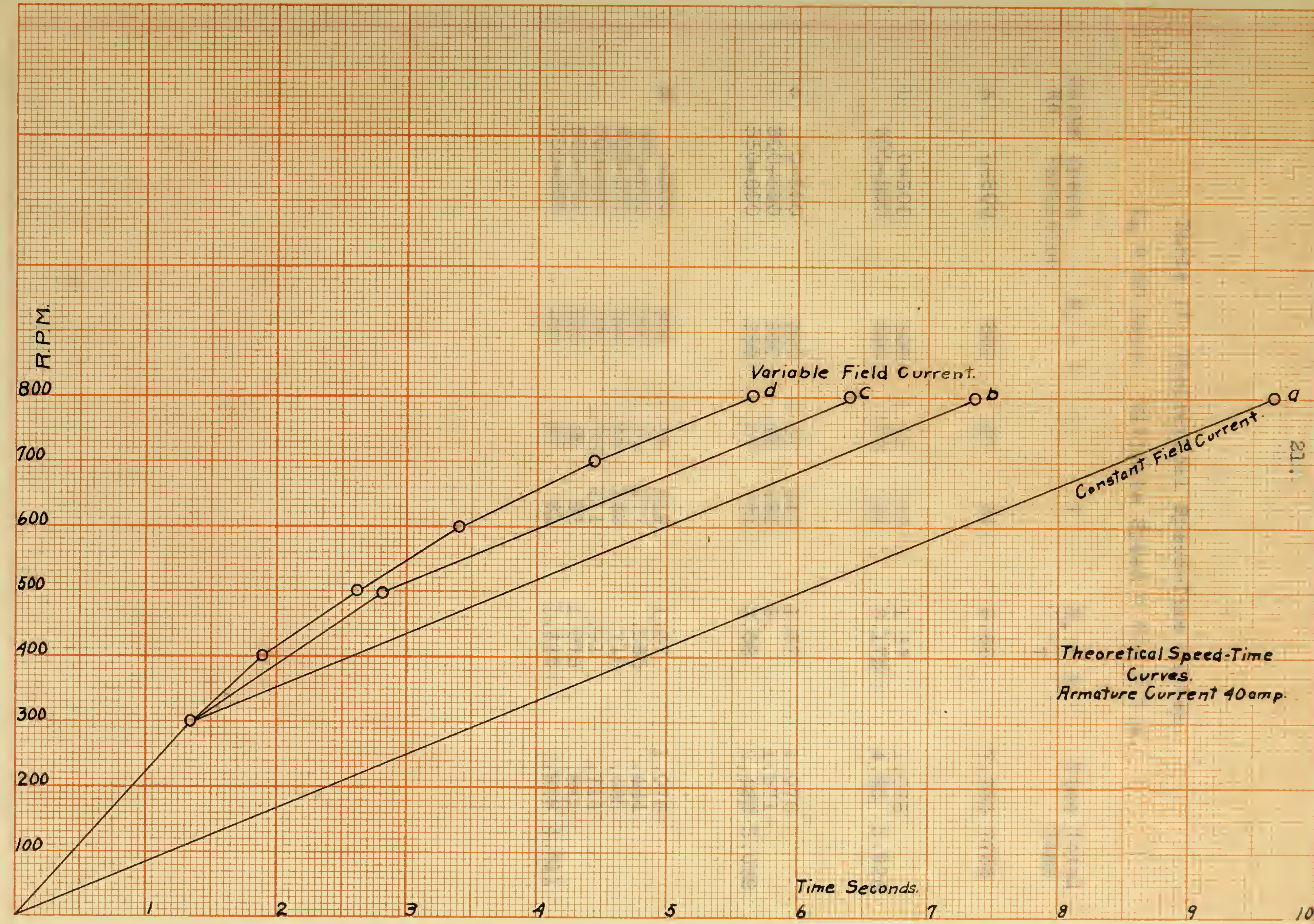

Torque lb. ft.
R.P.M.
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
800
700
600
500
400
300
200
100
I_a = 70 amp.
I_a = 60 amp.
I_a = 55 amp.
I_a = 50 amp.
I_a = 45 amp.
I_a = 40 amp.
I_a = 35 amp.
I_a = 30 amp.
I_a = 20 amp.
I_a = 10 amp.
R.P.M.
Torque - Field Current Curves
For Various Values of
Armature Current
and
R.P.M. - Field Current Curve
Field Current amp.

Table III

Theoretical Speed-Time Curves.

I_a = 40 Amperes   Ultimate Speed = 800 R.P.M.

Curve No.	Speed Variation	$N_2 - N_1$.	I_f.	T	$\frac{N_2 - N_1}{T}$	Time.	Total Time
a	0-800	800	.57	65	12.300	9.675	9.675
b	0-300	300	2.15	174	1.722	1.353	
	300-800	500	.57	65	7.695	6.040	7.395
c	0-300	300	2.15	174	1.722	1.353	
	300-500	200	.96	108	1.852	1.455	
	500-800	300	.57	65	4.620	3.628	6.438
d	0-300	300	2.15	174	1.722	1.353	
	300-400	100	1.25	140	.714	.560	
	400-500	100	.96	108	.926	.727	
	500-600	100	.75	89	1.123	.783	
	600-700	100	.65	75	1.322	1.048	
	700-800	100	.57	65	1.540	1.210	5.683


R.P.M.
800
700
600
500
400
300
200
100
1
2
3
4
5
6
7
8
9
10
Time Seconds.
Variable Field Current.
d
c
b
a
Constant Field Current.
Theoretical Speed-Time
Curves.
Armature Current 40 amp.

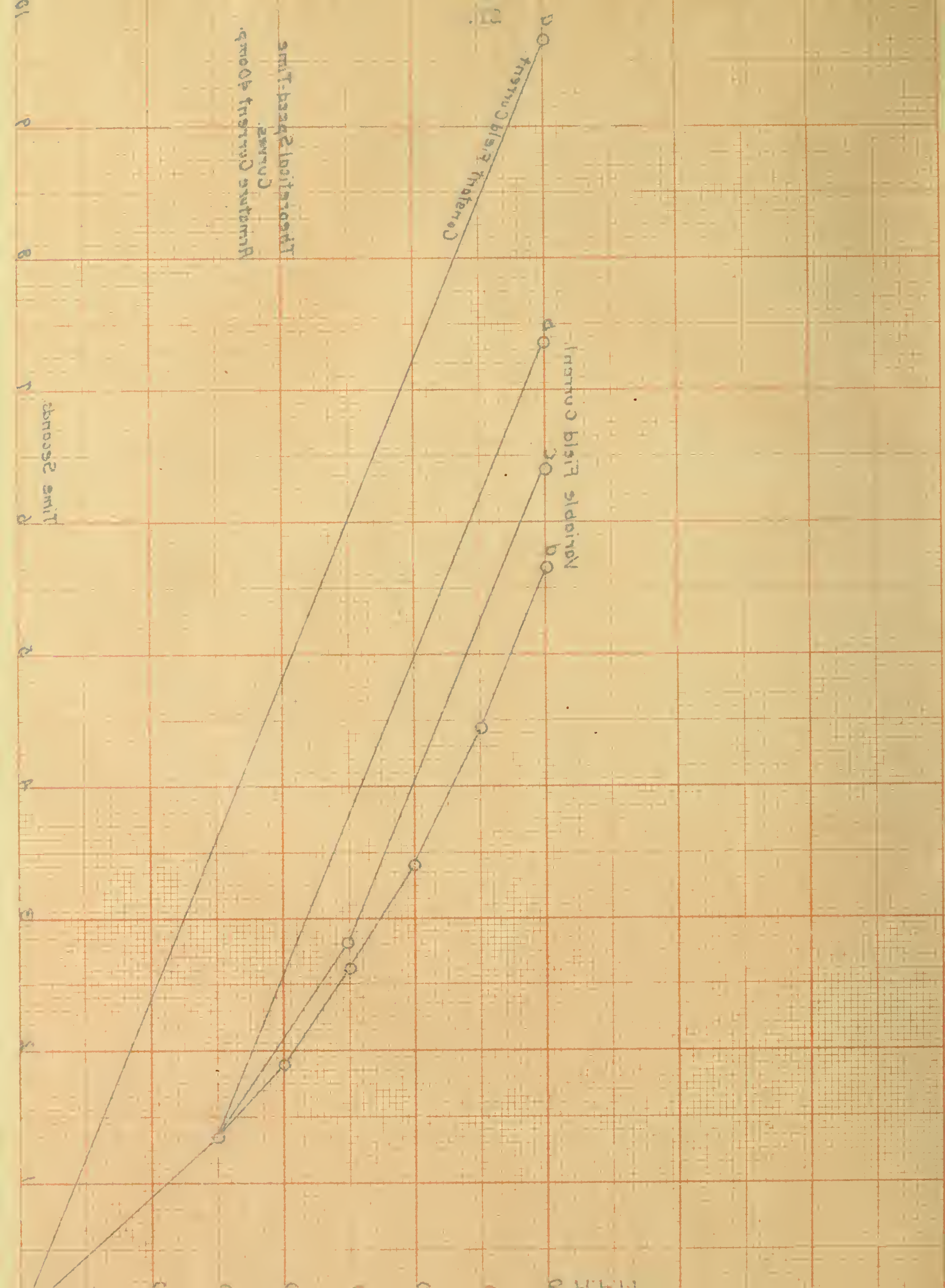
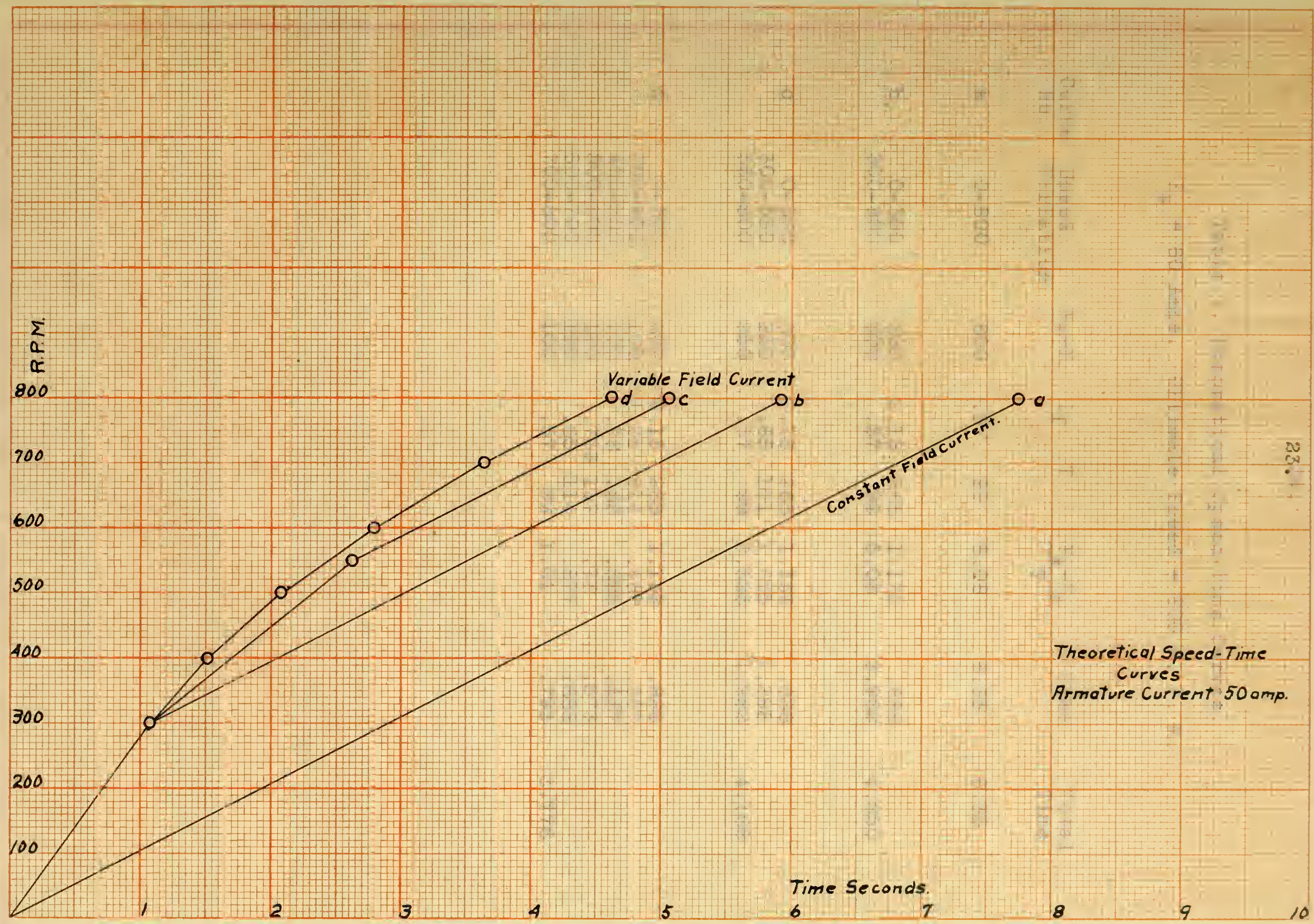

Theoretical Speed-Time
Curves
Armature Current 40amp.
Constant Field Current
Variable Field Current
Time Seconds

Table IV. Theoretical Speed-Time Curves.

I_a = 50 Amps. Ultimate Speed = 800 R.P.M.

Curve No.	Speed Variation	$N_2 - N_1$	I_f	T	$\frac{N_2 - N_1}{T}$	Time	Total Time
a	0-800	800	.57	81	9.88	7.755	7.755
b	0-300	300	2.15	219	1.37	1.076	
	300-800	500	.57	81	6.175	4.85	5.926
c	0-300	300	2.15	219	1.37	1.076	
	300-550	250	.85	125	2.	1.571	
	550-800	250	.57	81	3.08	2.422	5.069
d	0-300	300	2.15	219	1.37	1.076	
	300-400	100	1.25	177	.565	.444	
	400-500	100	.96	139	.719	.565	
	500-600	100	.753	111	.91	.714	
	600-700	100	.65	93	1.075	.843	
	700-800	100	.57	81	1.235	.969	4.611


R.P.M.
800
700
600
500
400
300
200
100
Variable Field Current
d
c
b
a
Constant Field Current.
Theoretical Speed-Time
Curves
Armature Current 50 amp.
Time Seconds.
1
2
3
4
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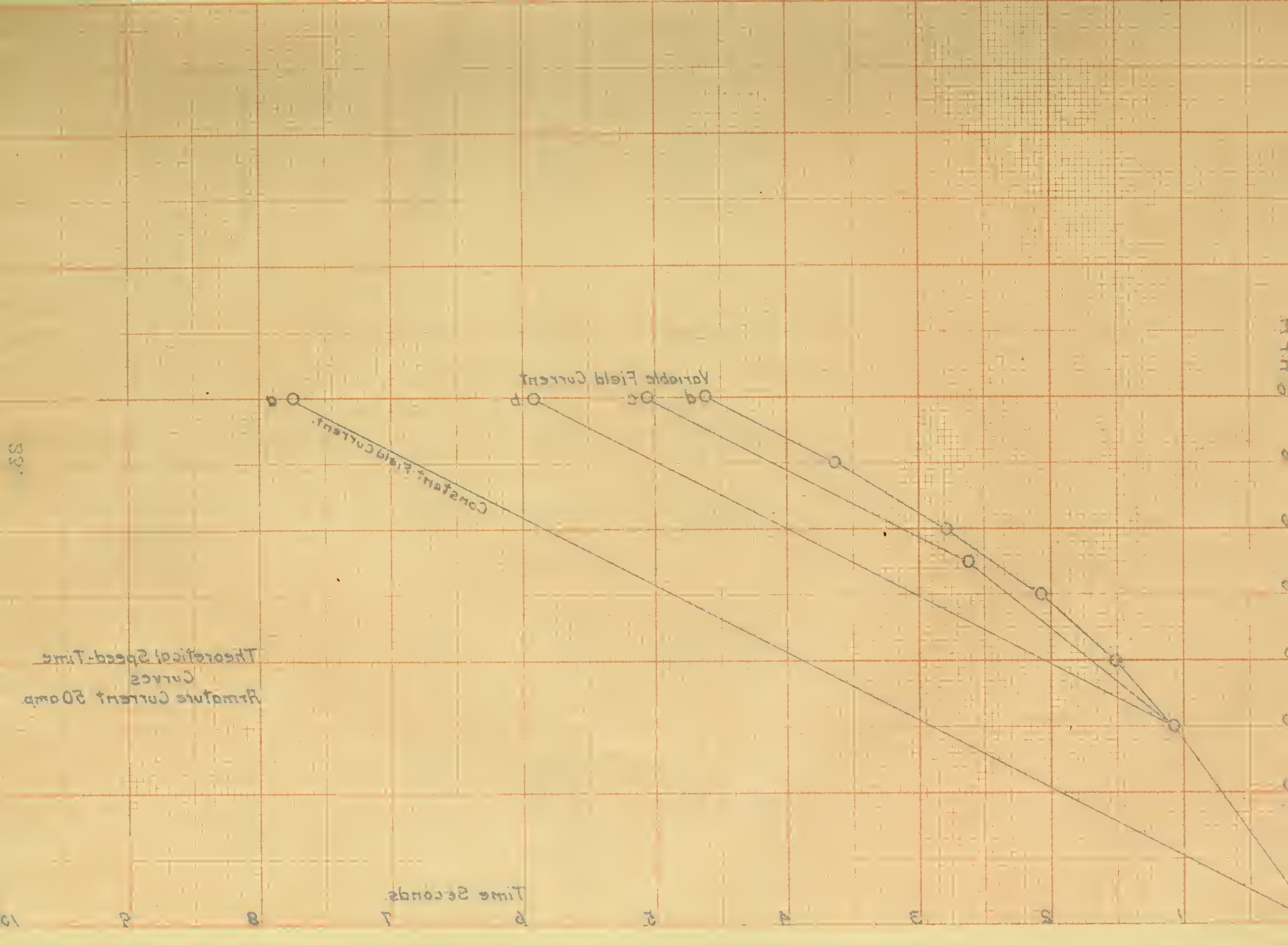


23.
Theoretical Speed-Time
Curves
Armature Current 50 amp.
Variable Field Current
Constant Field Current.
a
b
c
d
Time Seconds.
1
2
3
4
5
6
7
8
9
10

Table V. Theoretical Speed-Time Curves.

I_a = 60 Amps. Ultimate Speed = 800 R. P. M.

Curve No.	Speed Variation	N_2-N_1	I_f	T	$\frac{N_2-N_1}{T}$	Time	Total Time
a	0-800	800	.57	99	8.08	6.35	6.35
b	0-300	300	2.15	265	1.132	.888	
	300-800	500	.57	99	5.06	3.962	4.850
c	0-300	300	2.15	265	1.132	.888	
	300-550	250	.85	151	1.655	1.298	
	550-800	250	.57	99	2.525	1.982	4.168
d	0-300	300	2.15	265	1.132	.888	
	300-400	100	1.25	214	.467	.367	
	400-500	100	.96	168	.595	.467	
	500-600	100	.753	137	.73	.573	
	600-700	100	.65	114	.877	.688	
	700-800	100	.57	99	1.01	.793	3.776

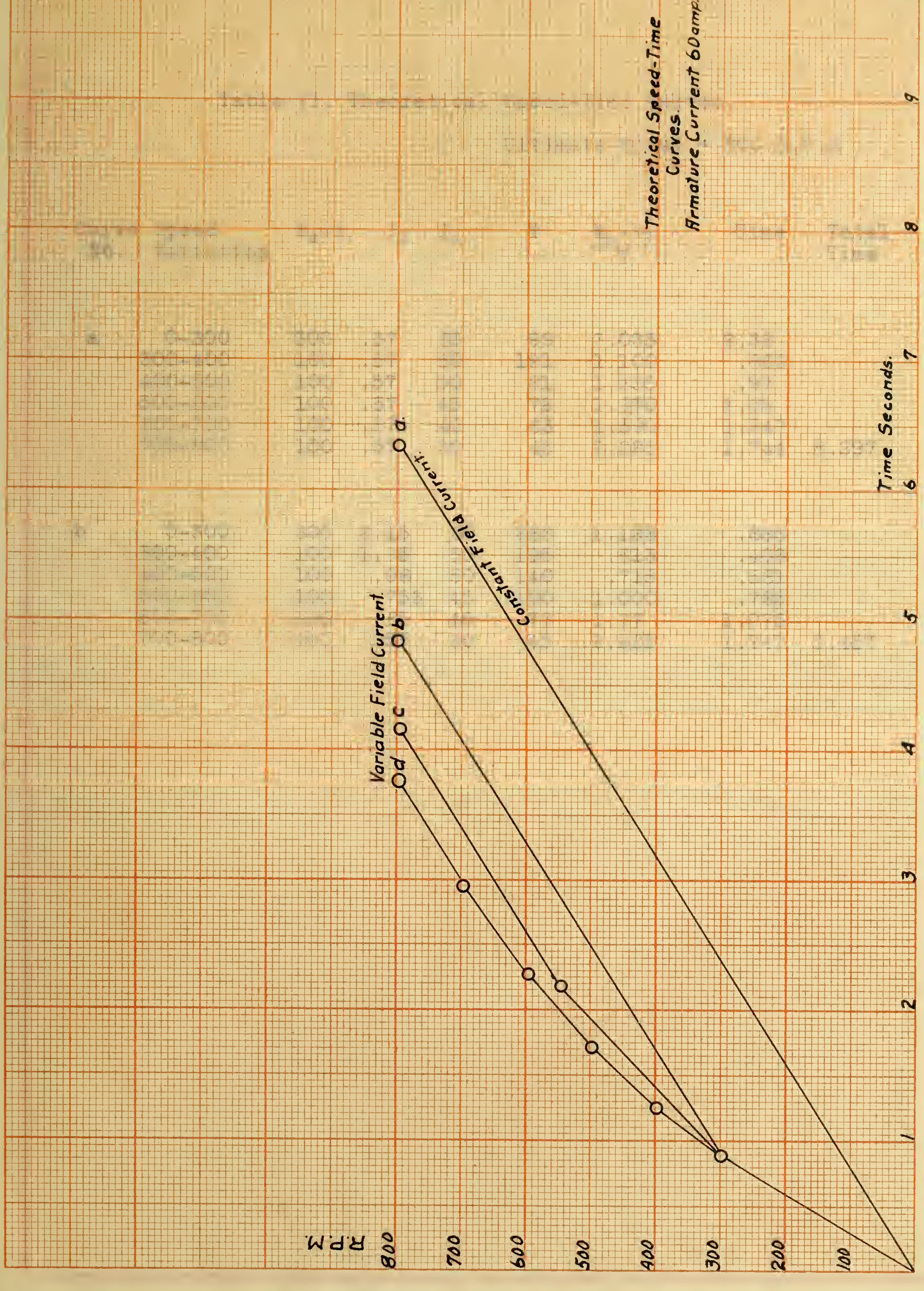
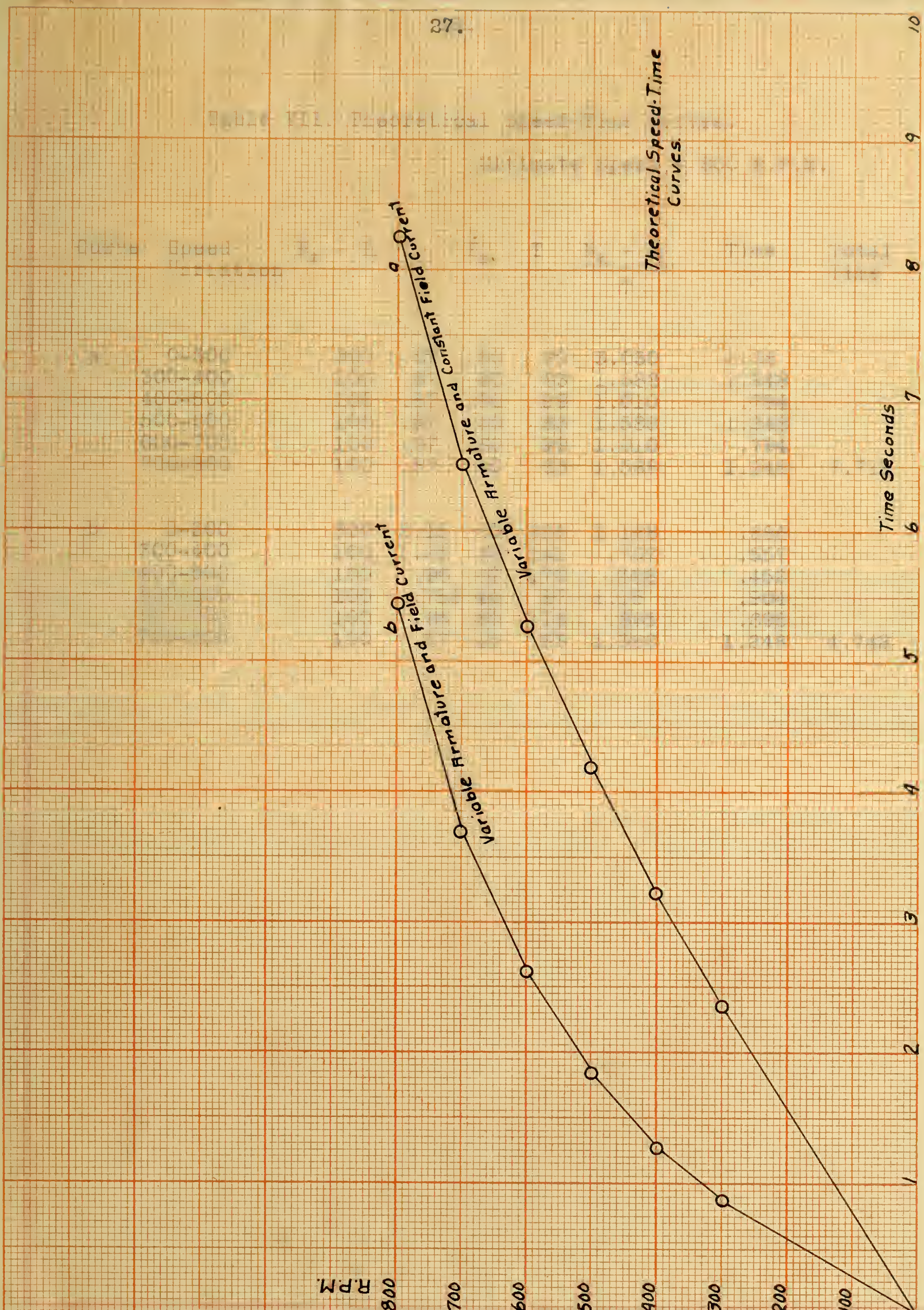

Theoretical Speed-Time
Curves.
Armature Current 60 amp.
Variable Field Current.
Constant Field Current.
a
b
c
d
R.P.M.
800
700
600
500
400
300
200
100
Time Seconds.
1
2
3
4
5
6
7
8
9
10

Table VI. Theoretical Speed-Time Curves.

Ultimate Speed = 800 R.P.M.

Curve No.	Speed Variation	N_2-N_1	I_f	I_a	T	$\frac{N_2-N_1}{T}$	Time	Total Time
a	0-300	300	.57	60	99	3.035	2.38	
	300-400	100	.57	50	191	1.100	.863	
	400-500	100	.57	50	81	1.235	.97	
	500-600	100	.57	45	72	1.390	1.09	
	600-700	100	.57	40	63	1.590	1.247	
	700-800	100	.57	30	45	2.225	1.744	8.297
b	0-300	300	2.15	60	266	1.128	.886	
	300-400	100	1.25	55	195	.513	.403	
	400-500	100	.96	50	140	.715	.561	
	500-600	100	.753	45	100	1.000	.785	
	600-700	100	.65	40	73	1.37	1.075	
	700-800	100	.57	30	45	2.225	1.747	5.457


Theoretical Speed-Time Curves.
a
Variable Armature and Constant Field Current
b
Variable Armature and Field Current
R.P.M.
800
700
600
500
400
300
200
100
Time Seconds
1
2
3
4
5
6
7
8
9
10

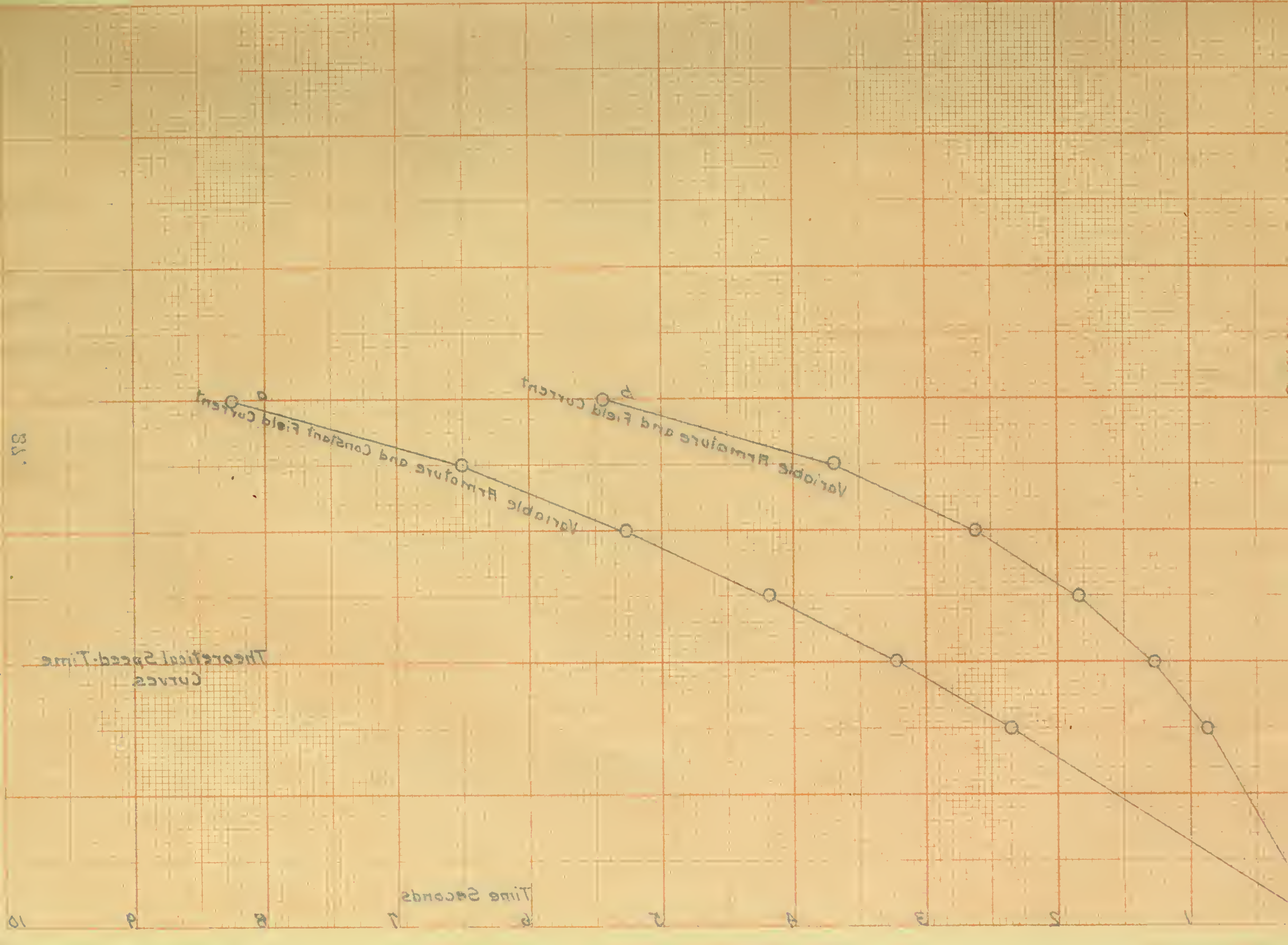
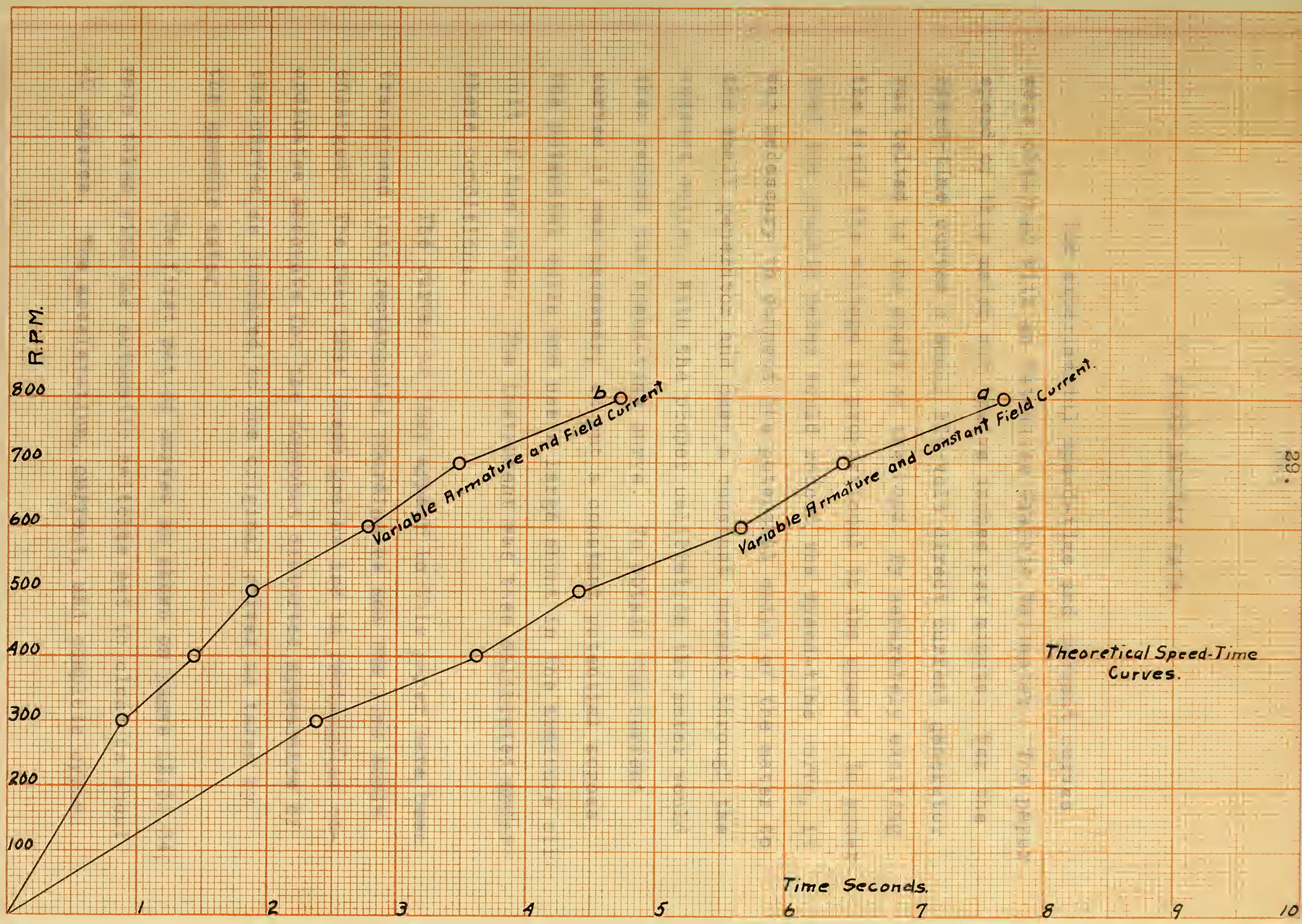
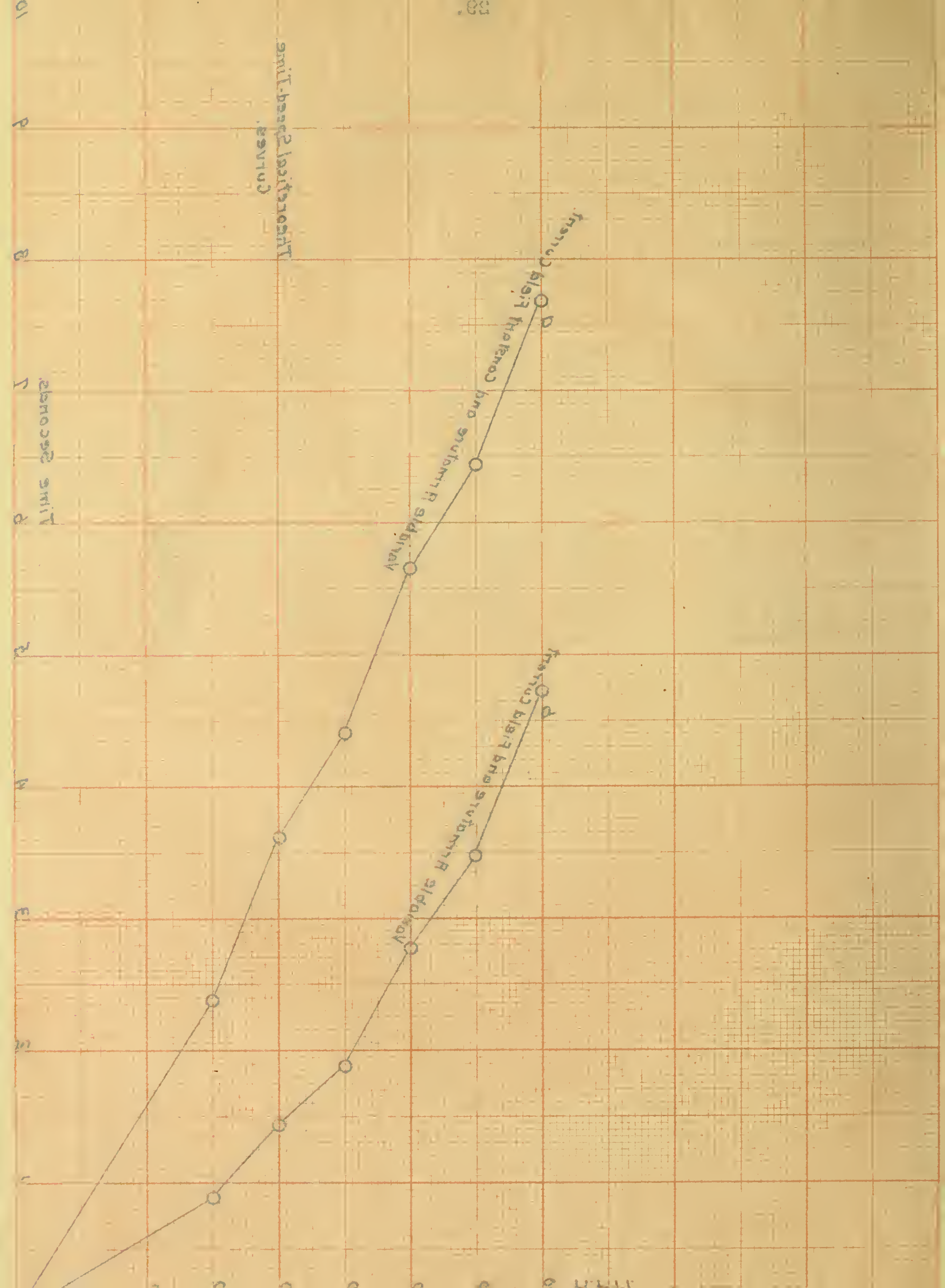

27.
Theoretical Speed-Time Curves
a
Variable Armature and Constant Field Current
b
Variable Armature and Field Current
Time Seconds
1
2
3
4
5
6
7
8
9
10

Table VII. Theoretical Speed-Time Curves.

Ultimate Speed = 800 R.P.M.

Curve	Speed Variation	$N_2 - N_1$	I_f	I_a	T	$\frac{N_2 - N_1}{T}$	Time	Total Time
a	0-300	300	.57	60	99	3.030	2.38	
	300-400	100	.57	40	63	1.588	1.248	
	400-500	100	.57	60	99	1.010	.794	
	500-600	100	.57	40	63	1.588	1.248	
	600-700	100	.57	60	99	1.010	.794	
	700-800	100	.57	40	63	1.588	1.248	7.712
b	0-300	300	2.15	60	266	1.128	.886	
	300-400	100	1.25	40	141	.707	.557	
	400-500	100	.96	60	170	.588	.452	
	500-600	100	.753	40	87	1.15	.904	
	600-700	100	.65	60	113	.885	.695	
	700-800	100	.57	40	63	1.588	1.248	4.742


R.P.M.
800
700
600
500
400
300
200
100
b
Variable Armature and Field Current
a
Variable Armature and Constant Field Current.
Theoretical Speed-Time Curves.
Time Seconds.
1
2
3
4
5
6
7
8
9
10


38.
Theoretical Speed-Time Curves.
Time Seconds
Variable Armature and Constant Field Current
Variable Armature and Field Current

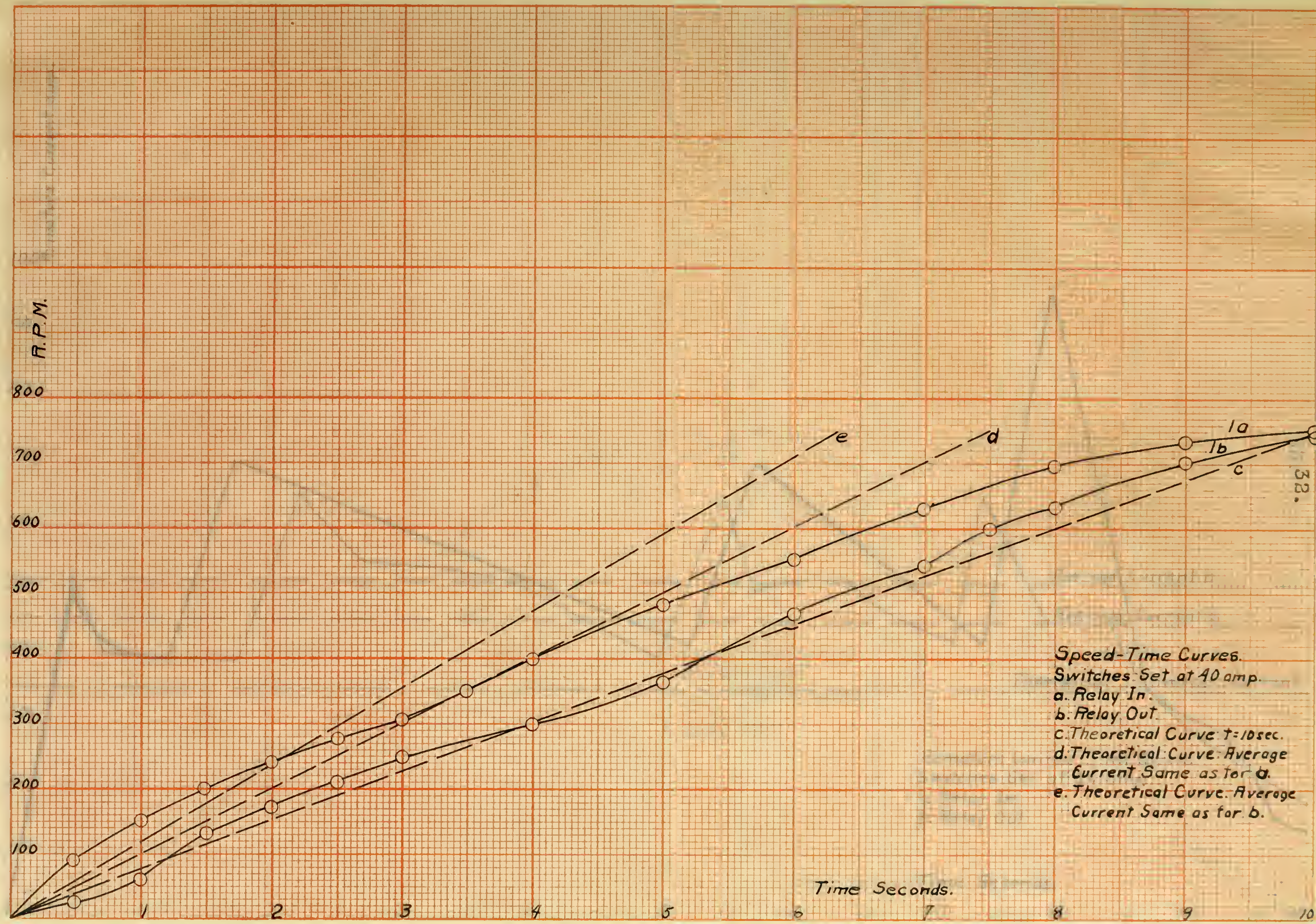
V. EXPERIMENTAL DATA.

The experimental speed-time and current curves were obtained with an Esterline Graphic Wattmeter. The paper speed of this meter was twelve inches per minute. For the speed-time curves a small 110 volt direct current generator was belted to the shaft of the load. By separately exciting the field the voltage is proportional to the speed. In order that the graphic meter would record the speed-time curve, it was necessary to connect the potential coils of the meter to the small generator and pass a constant current through the current coils. With the proper calibration the meter would then record the speed-time curve. To obtain the current curves it was necessary to put a constant potential across the potential coils and use a large shunt in the armature circuit of the motor. The instrument was then calibrated under these conditions.

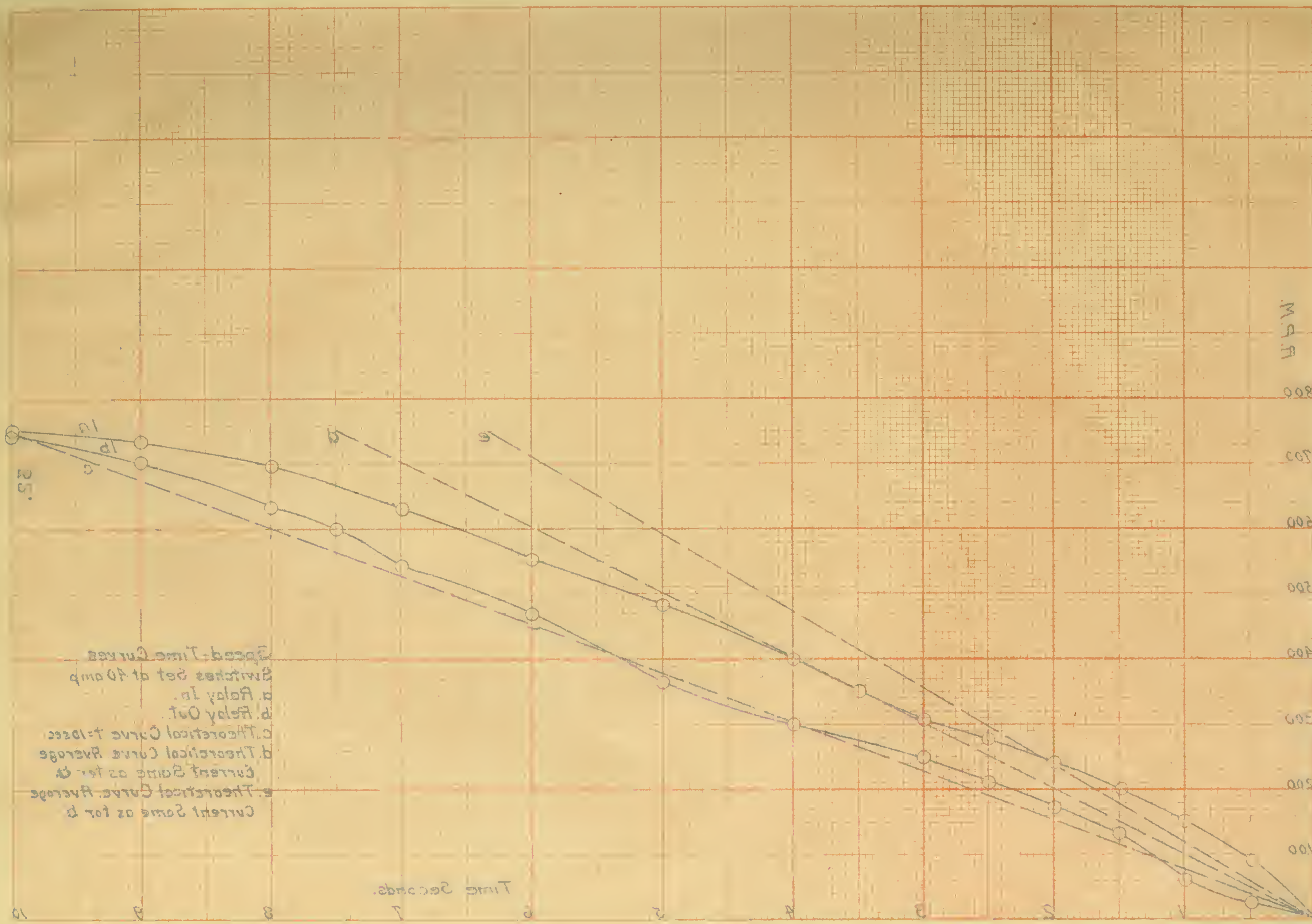
The curves as they appear in this paper have been transposed into rectangular coordinates and the time scale enlarged. The fact that these graphs are in rectangular coordinates accounts for the somewhat distorted appearance of the curves as compared to the original curves as taken by the graphic meter.

The first set of curves as shown on pages 32,33,34, were taken with the automatic switches set to close as about 40 amperes. The acceleration, current, and complete cycle

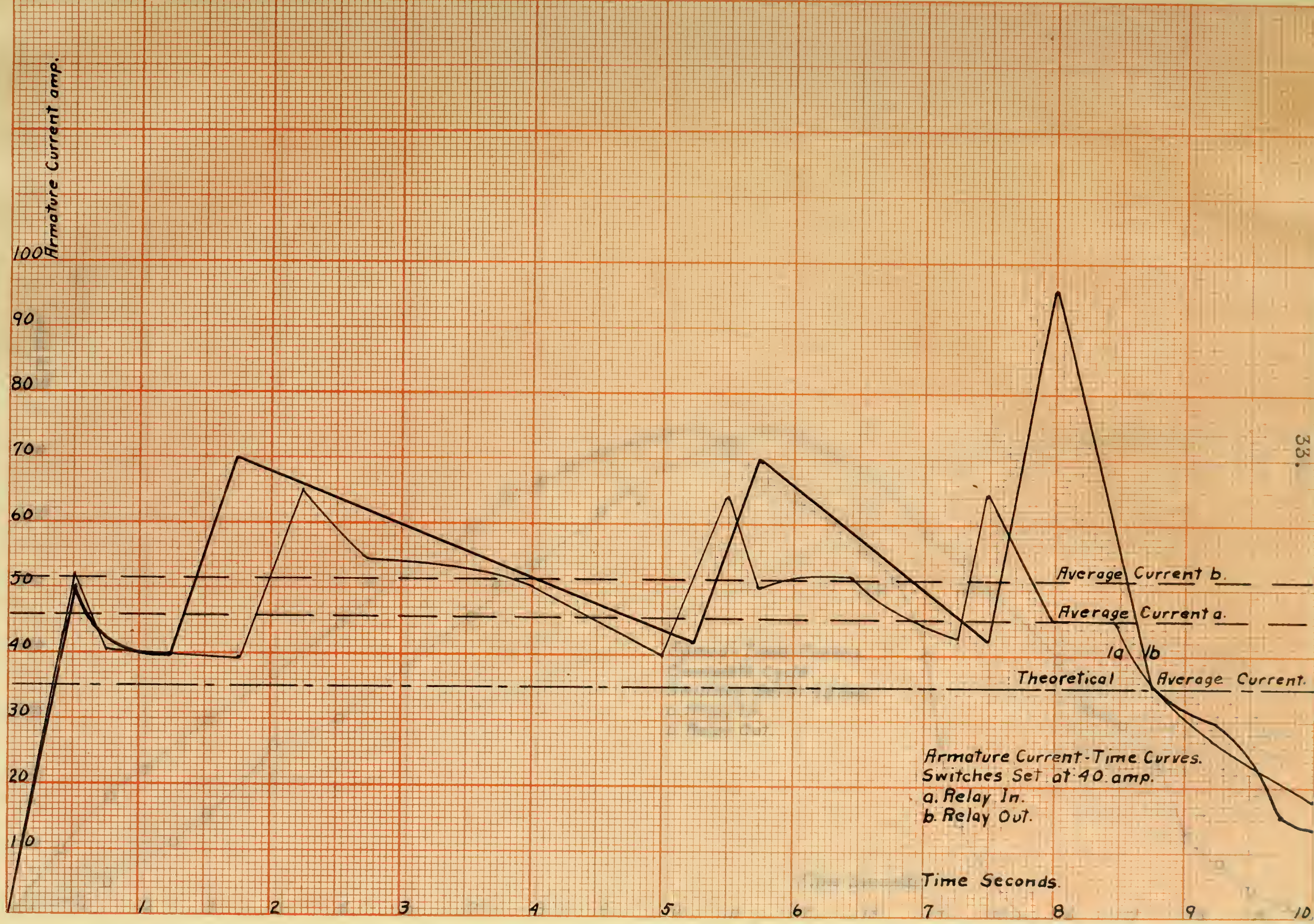
curves were taken. Then the setting of the switches was changed so that they would close at about 45 amperes and similar curves taken, pages 35,36,37The third set was taken with the switches set to close at about full·load current value of 55 amperes, pages 38-40. The switches here referred to are S_1 , S_2, S_3, page 4. . Two sets of curves were taken for each setting of the switches, one with the field relay in, and the other, with the relay out. In all cases the final speed of the load was taken at 750 R.P.M. so that all curves were obtained under as nearly the same conditions in regard to ultimate speed as was possible. In these sets of curves the letter (a) refers to the curves with the relay in, and (b) with the relay out.

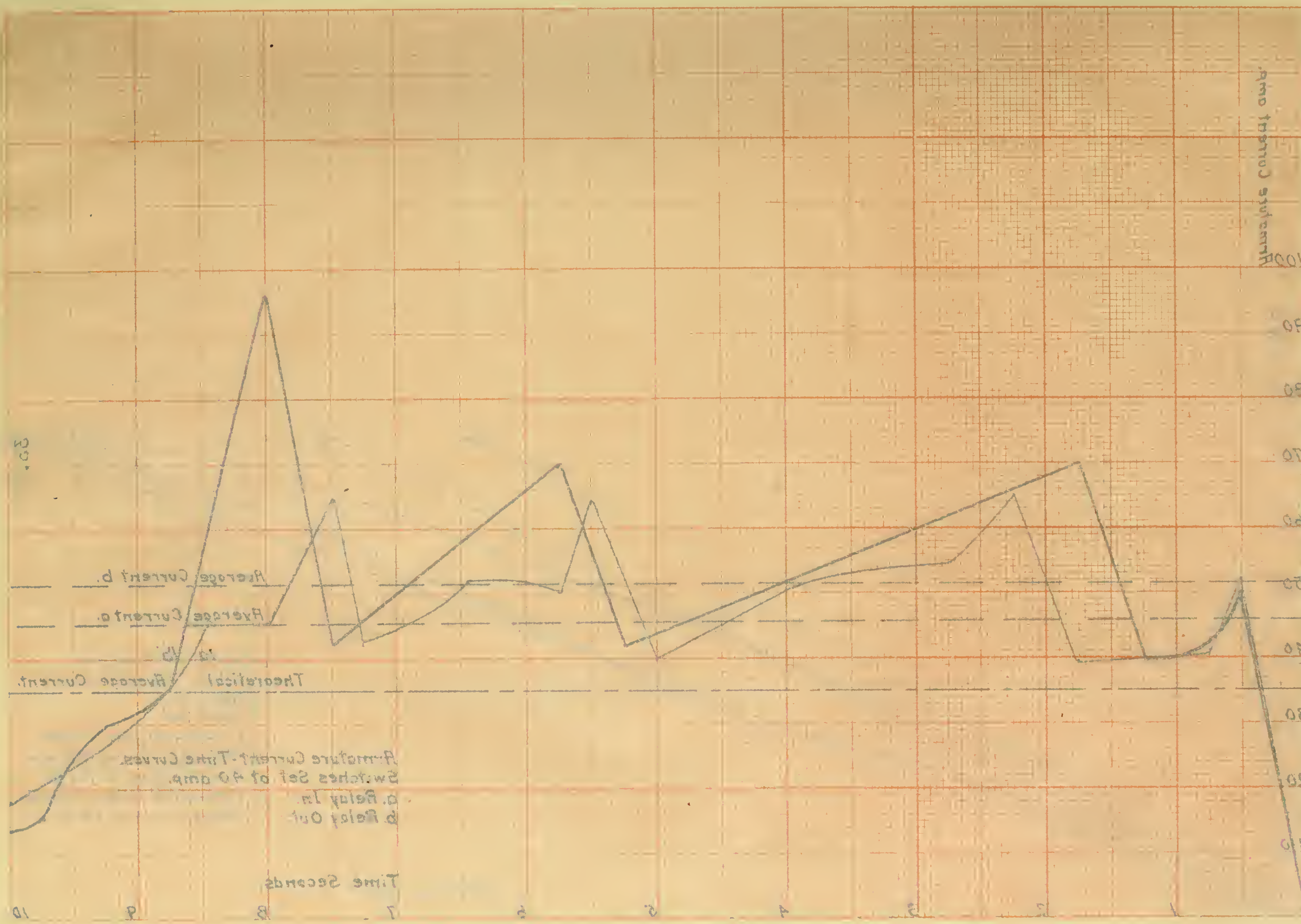


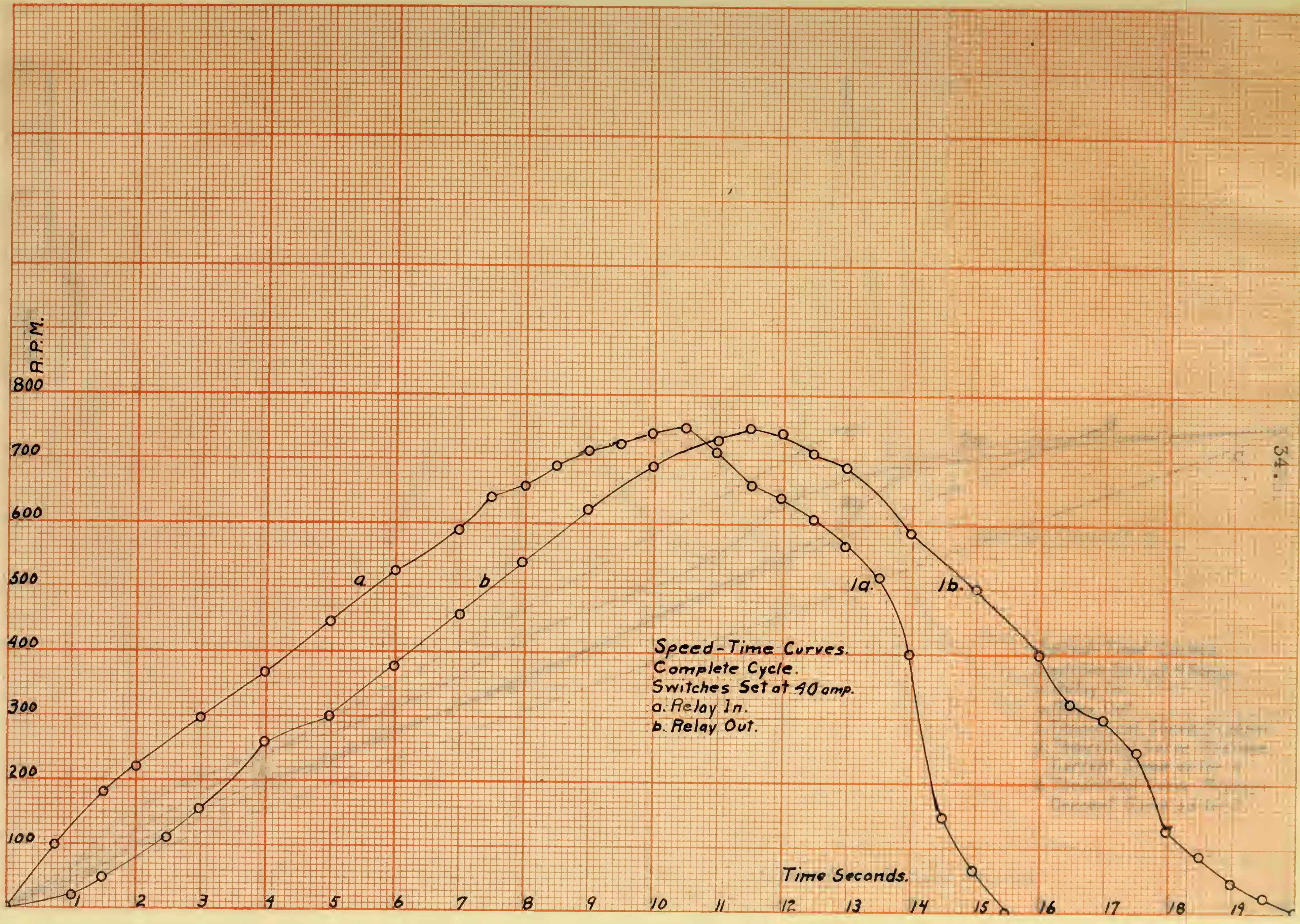
R.P.M.
800
700
600
500
400
300
200
100
1a
1b
c
d
e
1
2
3
4
5
6
7
8
9
10
Time Seconds.
Speed-Time Curves.
Switches Set at 40 amp.
a. Relay In.
b. Relay Out.
c. Theoretical Curve t=10sec.
d. Theoretical Curve. Average Current Same as for a.
e. Theoretical Curve. Average Current Same as for b.

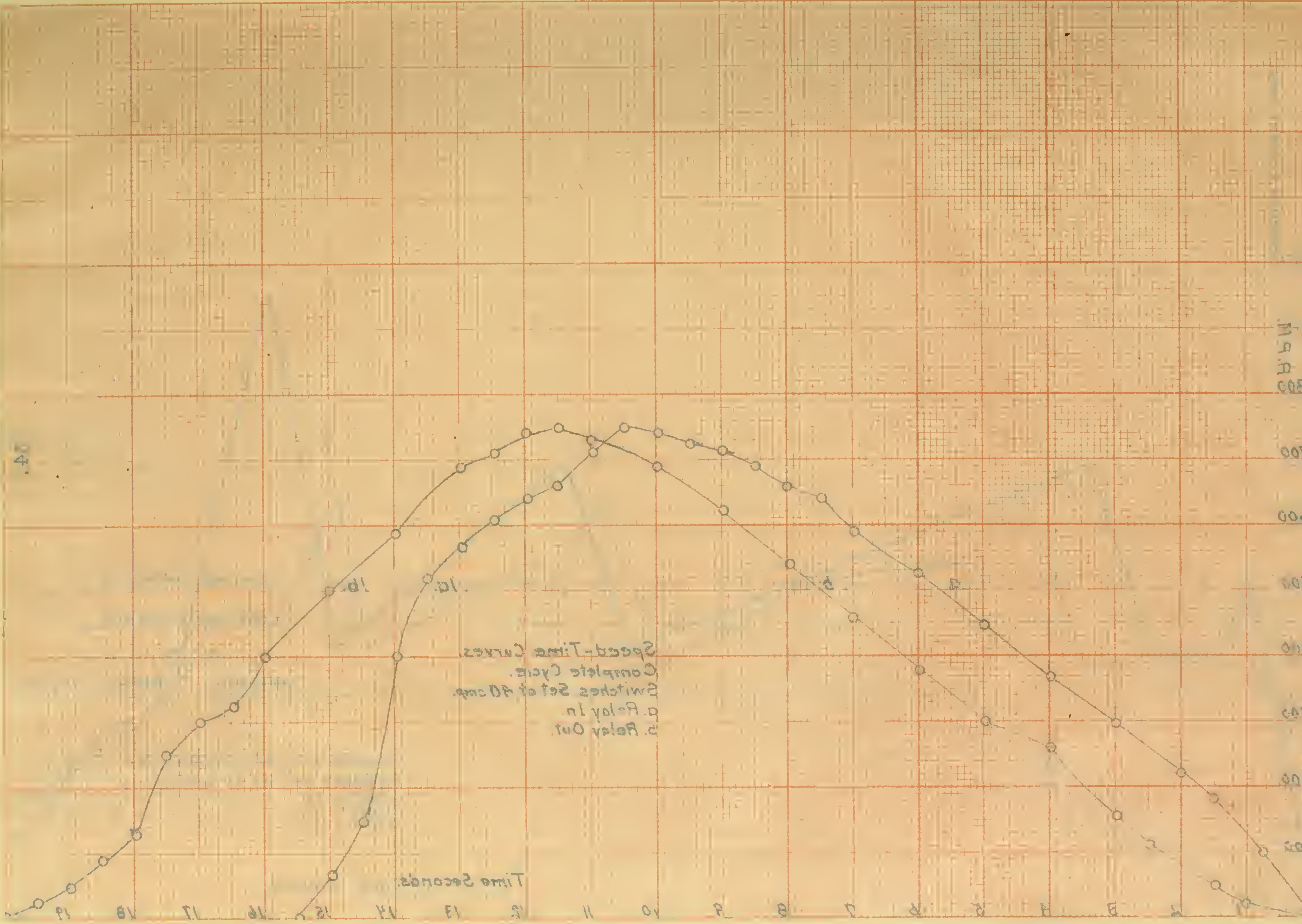


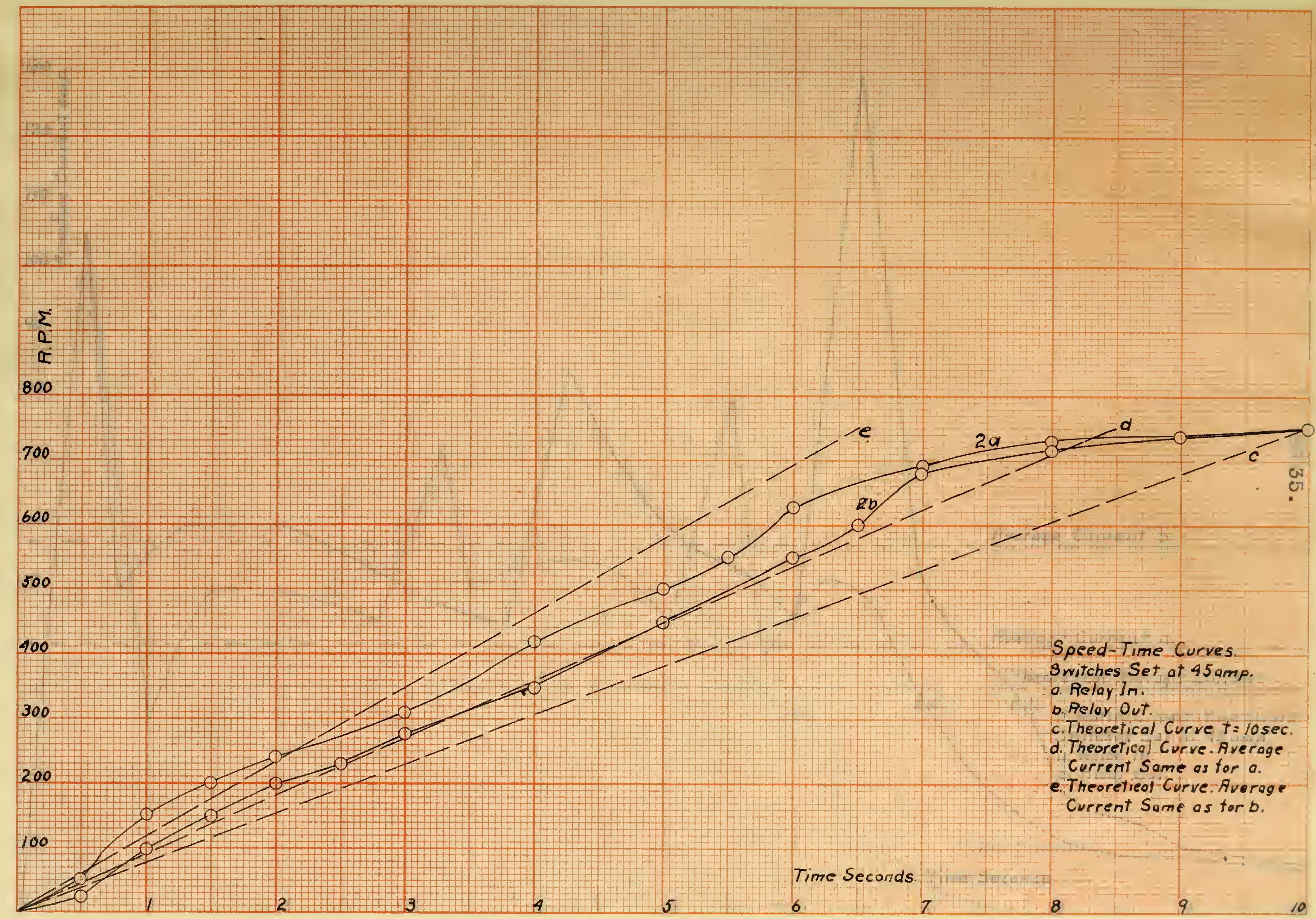
52.
R.P.M.
Time Seconds.
Speed-Time Curves
Switches Set at 40 amp
a. Relay In.
b. Relay Out.
c. Theoretical Curve T=10sec
d. Theoretical Curve. Average Current Same as for a
e. Theoretical Curve. Average Current Same as for b

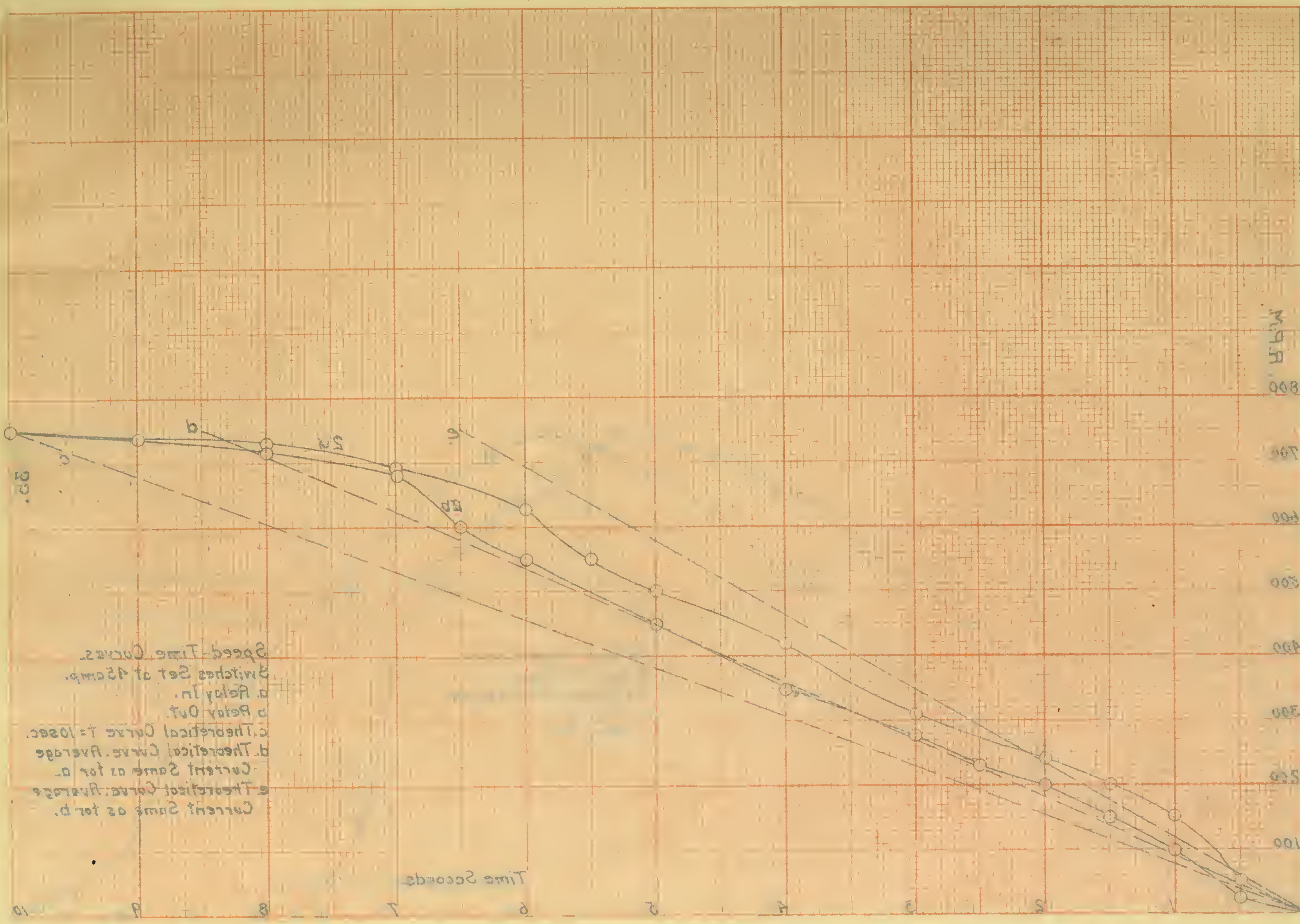

Armature Current amp.
100
90
80
70
60
50
40
30
20
10
Average Current b.
Average Current a.
1a
1b
Theoretical Average Current.
Armature Current-Time Curves.
Switches Set at 40 amp.
a. Relay In.
b. Relay Out.
Time Seconds.
1
2
3
4
5
6
7
8
9
10


Armature Current amp.
Time Seconds
Average Current b.
Average Current a.
Theoretical Average Current.
Armature Current-Time Curves.
Switches Set at 40 amp.
a. Relay In.
b. Relay Out

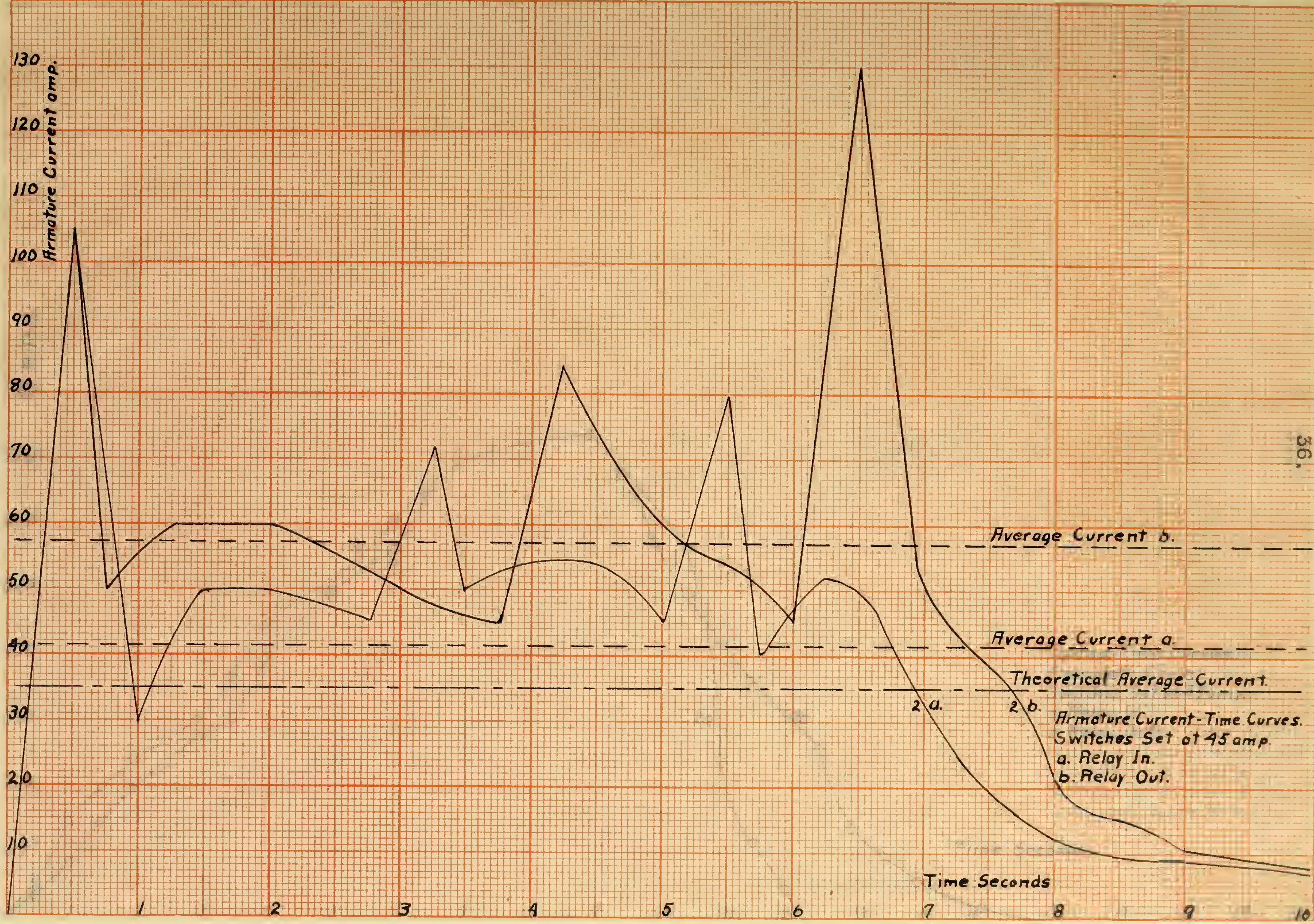

R.P.M.
800
700
600
500
400
300
200
100
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
a.
b
1a.
1b.
Speed-Time Curves.
Complete Cycle.
Switches Set at 40 amp.
a. Relay In.
b. Relay Out.
Time Seconds.


Speed-Time Curves.
Complete Cycle.
Switches Set at 40 amp.
a. Relay In.
b. Relay Out.
1a.
1b.
a
b
c
Time Seconds.
R.P.M.
100
200
300
400
500
600
700
800
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19

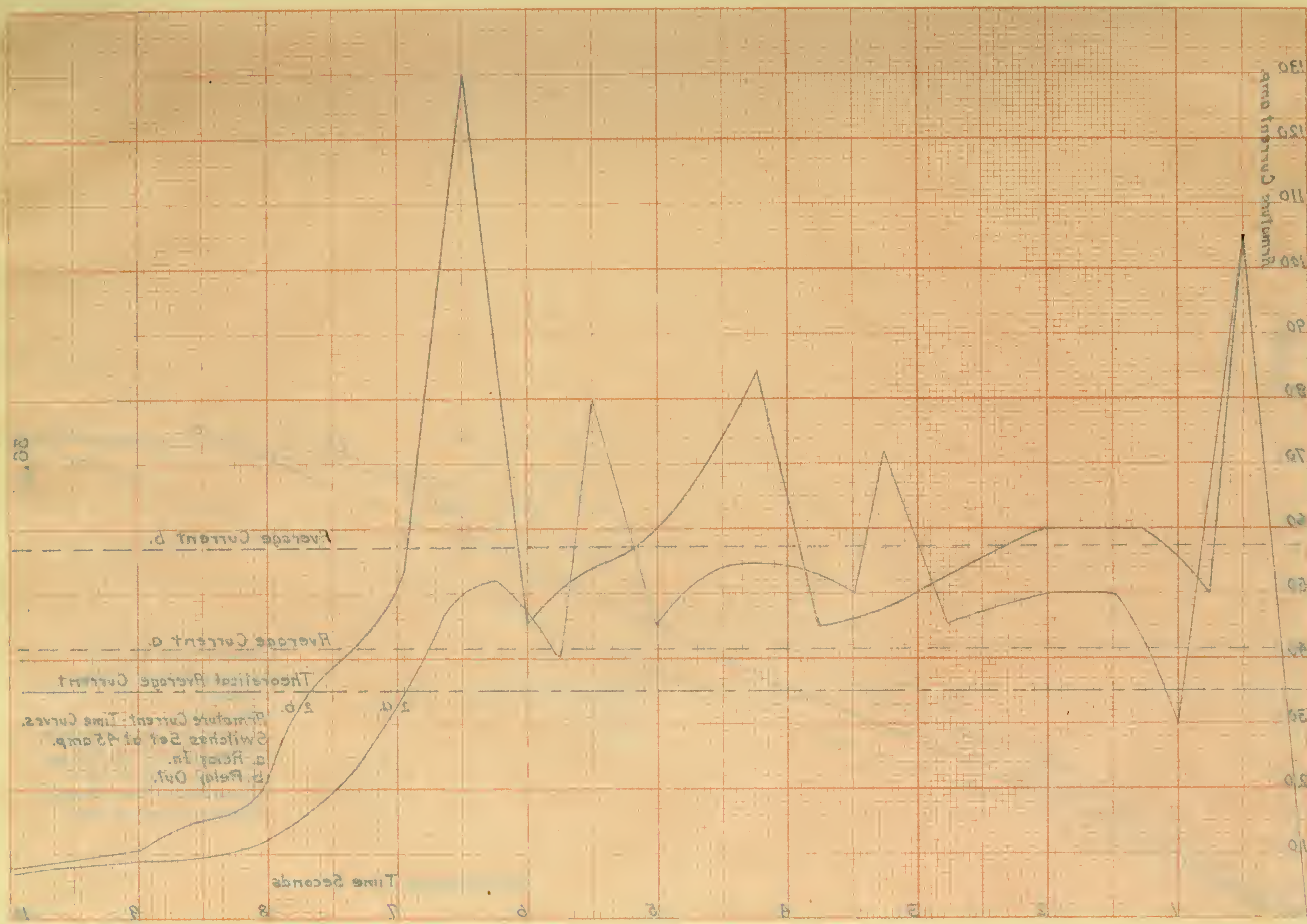

35.
Speed-Time Curves.
Switches Set at 45 amp.
a. Relay In.
b. Relay Out.
c. Theoretical Curve t = 10 sec.
d. Theoretical Curve. Average Current Same as for a.
e. Theoretical Curve. Average Current Same as for b.
R.P.M.
Time Seconds.
2a
2b
c
d
e
800
700
600
500
400
300
200
100
1
2
3
4
5
6
7
8
9
10



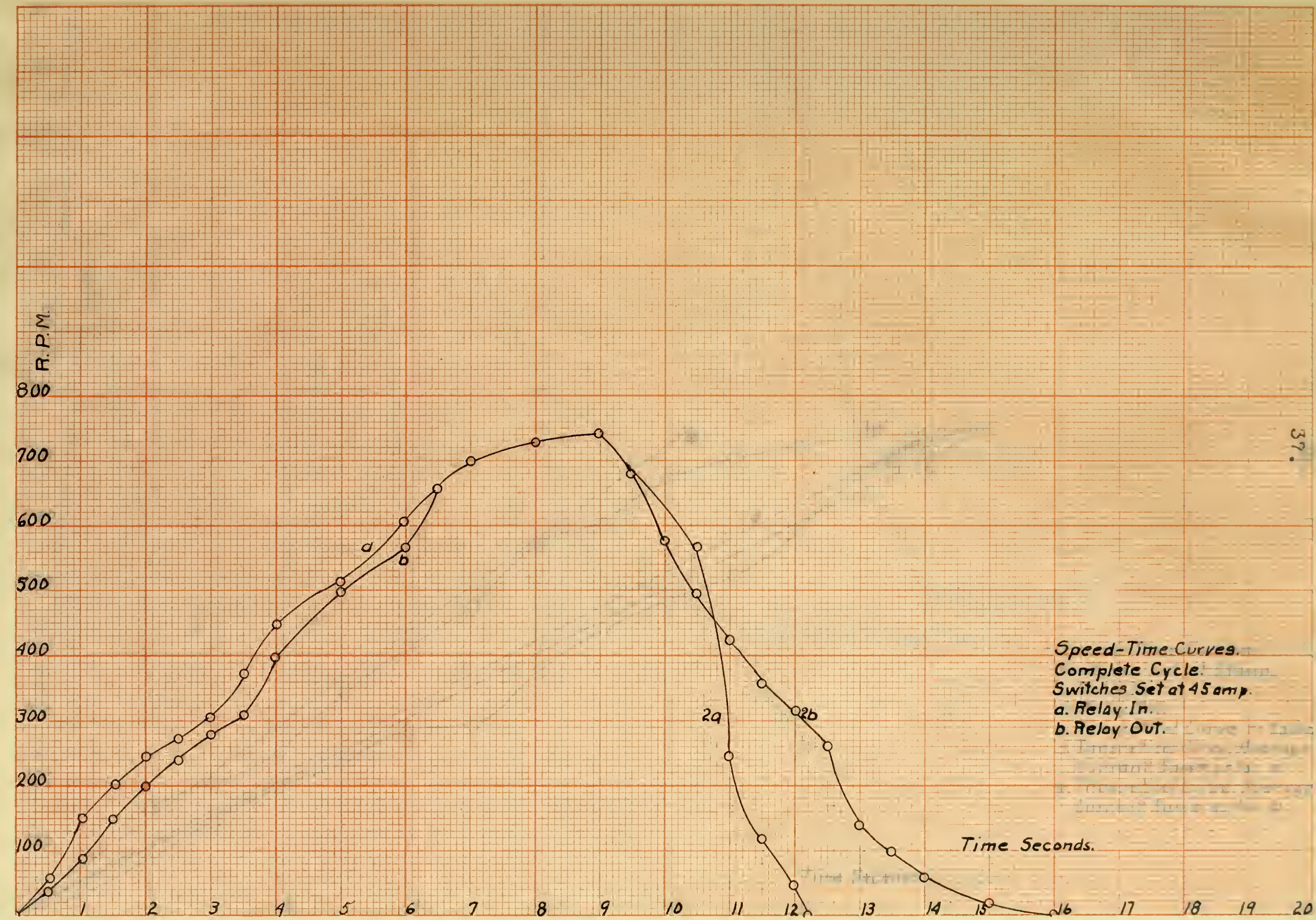
Speed-Time Curves.
Switches Set at 45amp.
a. Relay In.
b. Relay Out.
c. Theoretical Curve T=10sec.
d. Theoretical Curve. Average Current Same as for a.
e. Theoretical Curve. Average Current Same as for b.
Time Seconds
R.P.M.
100
200
300
400
500
600
700
800
1
2
3
4
5
6
7
8
9
10



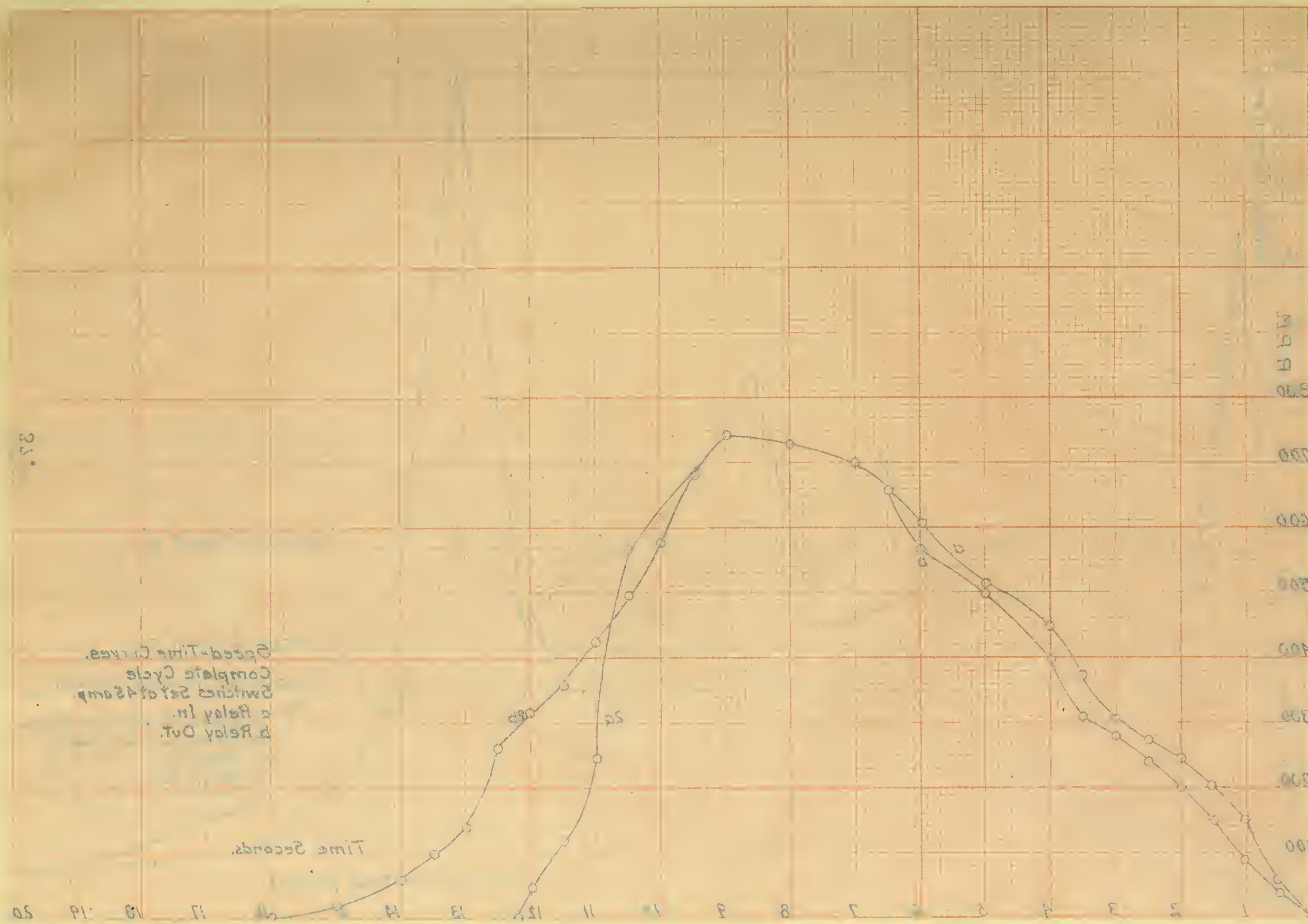
Armature Current amp.
130
120
110
100
90
80
70
60
50
40
30
20
10
Average Current b.
Average Current a.
Theoretical Average Current.
2 a.
2 b.
Armature Current-Time Curves.
Switches Set at 45 amp.
a. Relay In.
b. Relay Out.
Time Seconds
1
2
3
4
5
6
7
8
9
10

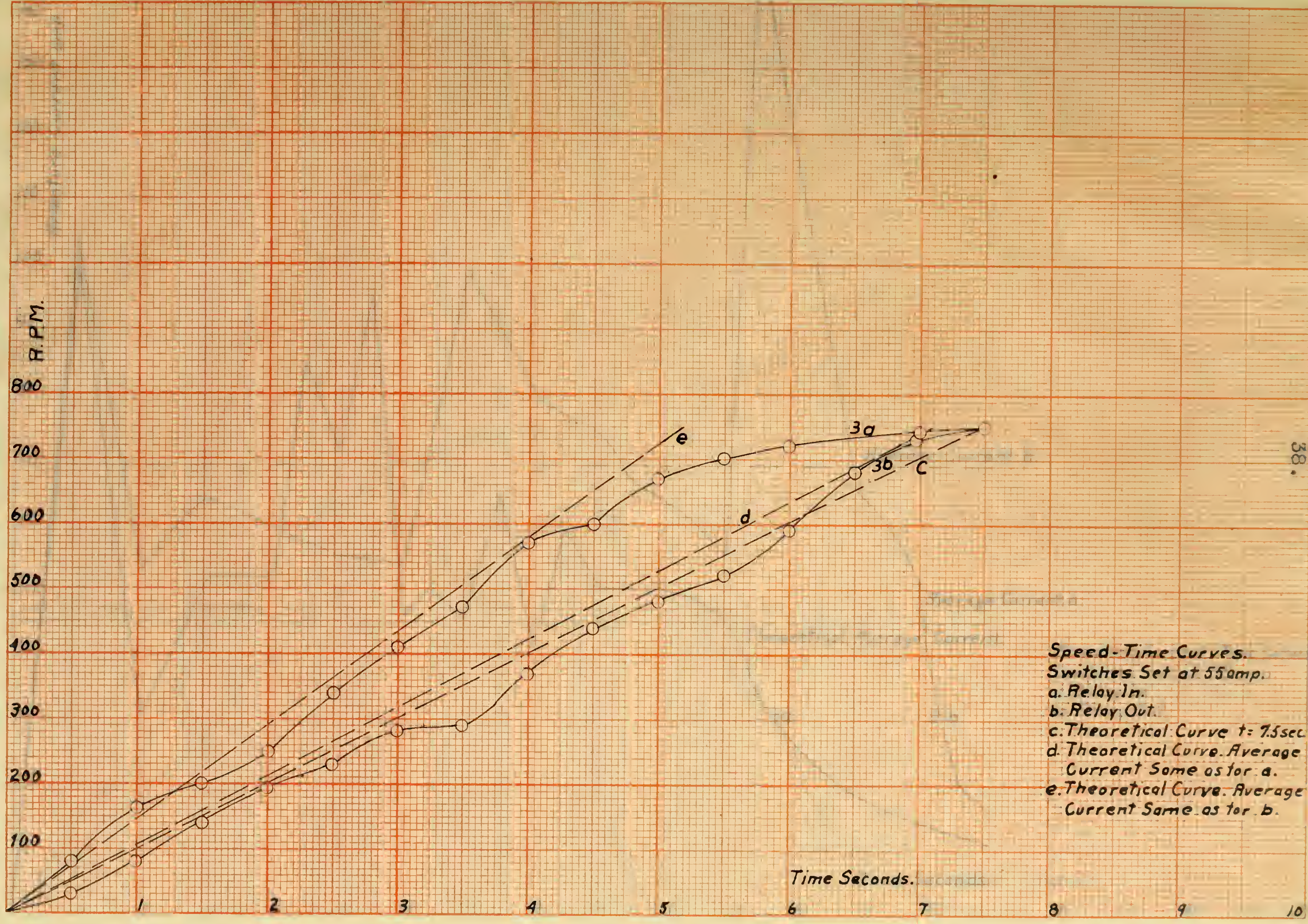


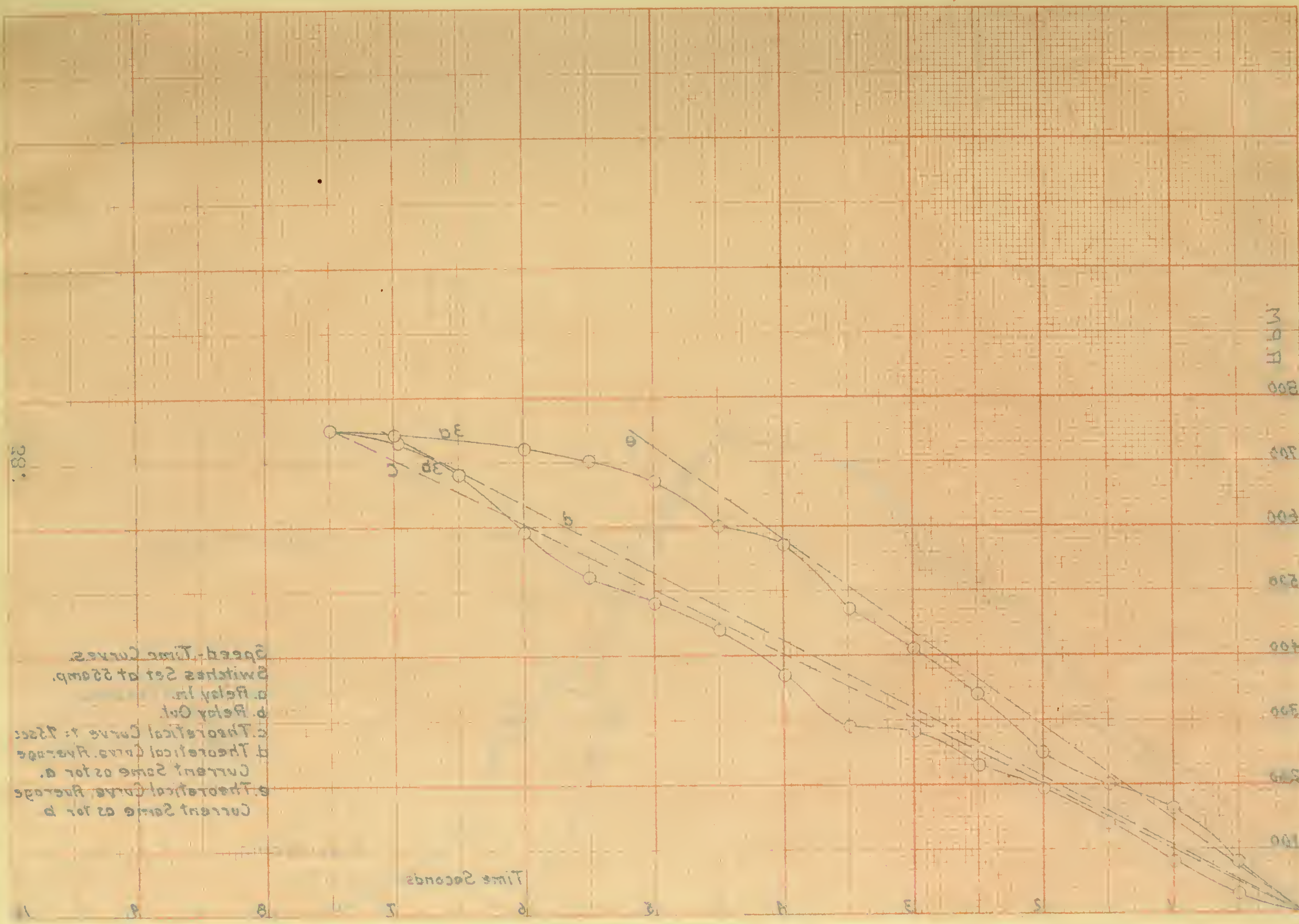
Armature Current amp
Average Current b.
Average Current a.
Theoretical Average Current
Armature Current-Time Curves.
Switches Set at 45 amp.
a. Relay In.
b. Relay Out.
Time Seconds

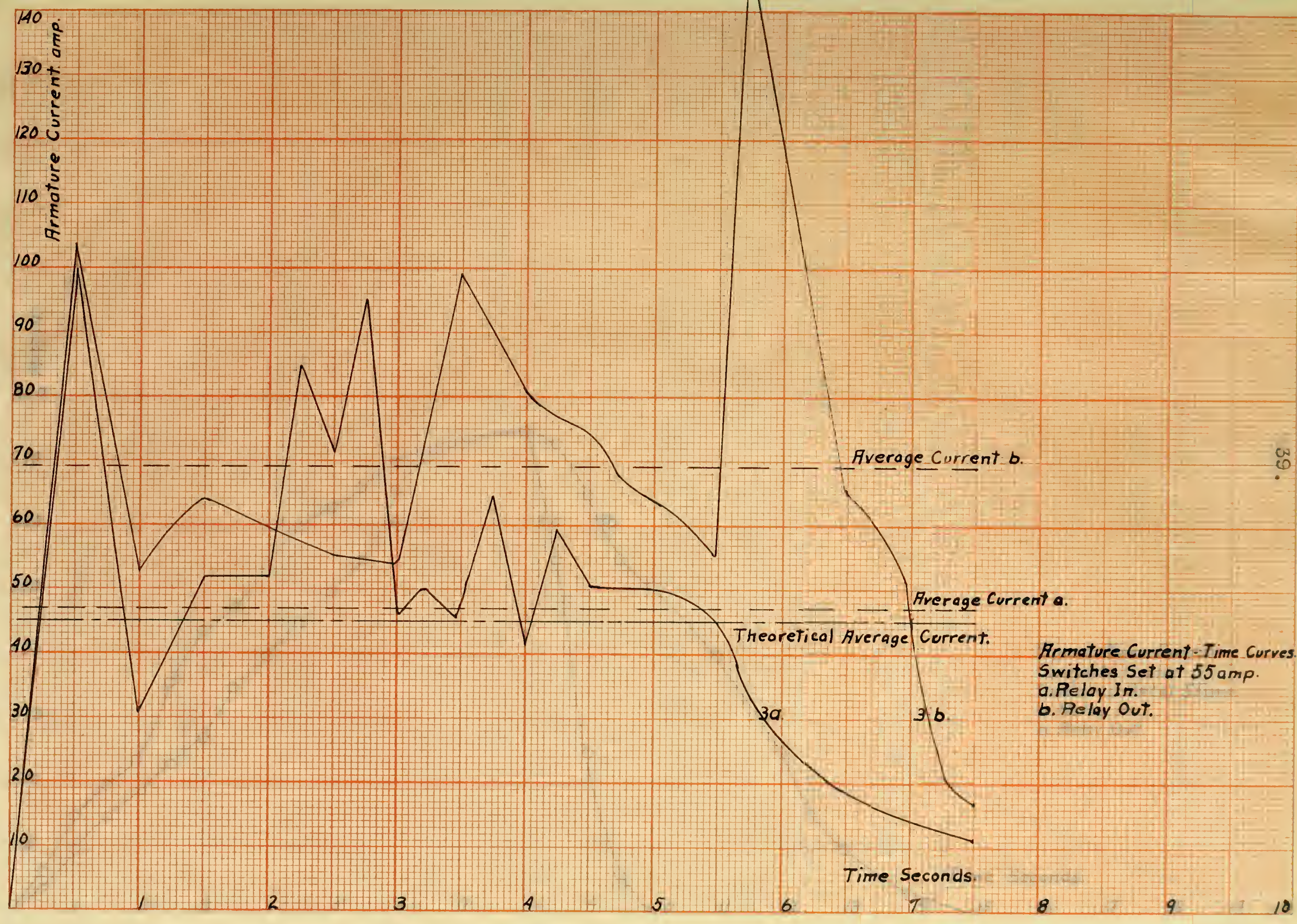


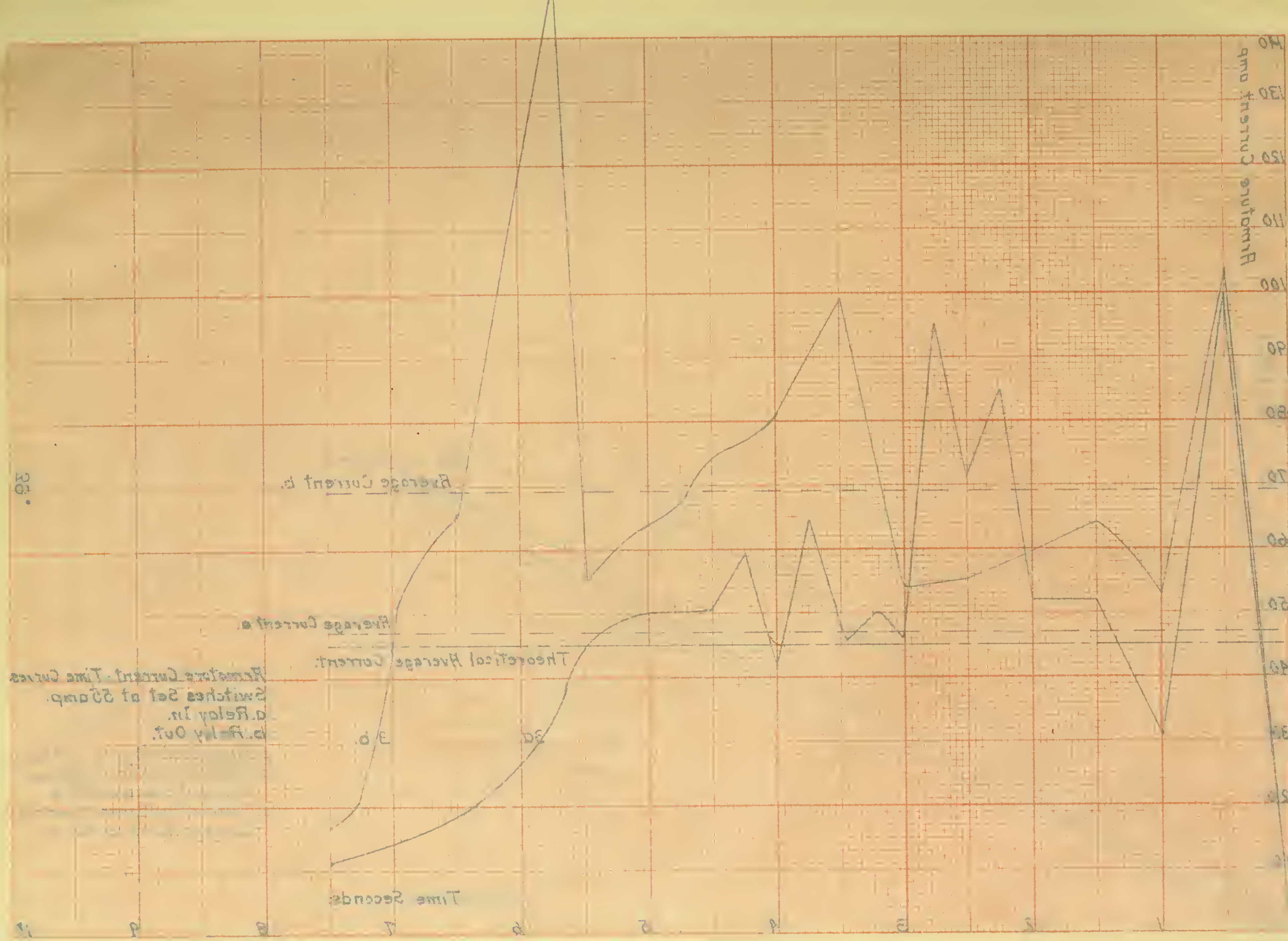
37.
R.P.M.
800
700
600
500
400
300
200
100
a
b
2a
2b
Speed-Time Curves.
Complete Cycle.
Switches Set at 45 amp.
a. Relay In.
b. Relay Out.
Time Seconds.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

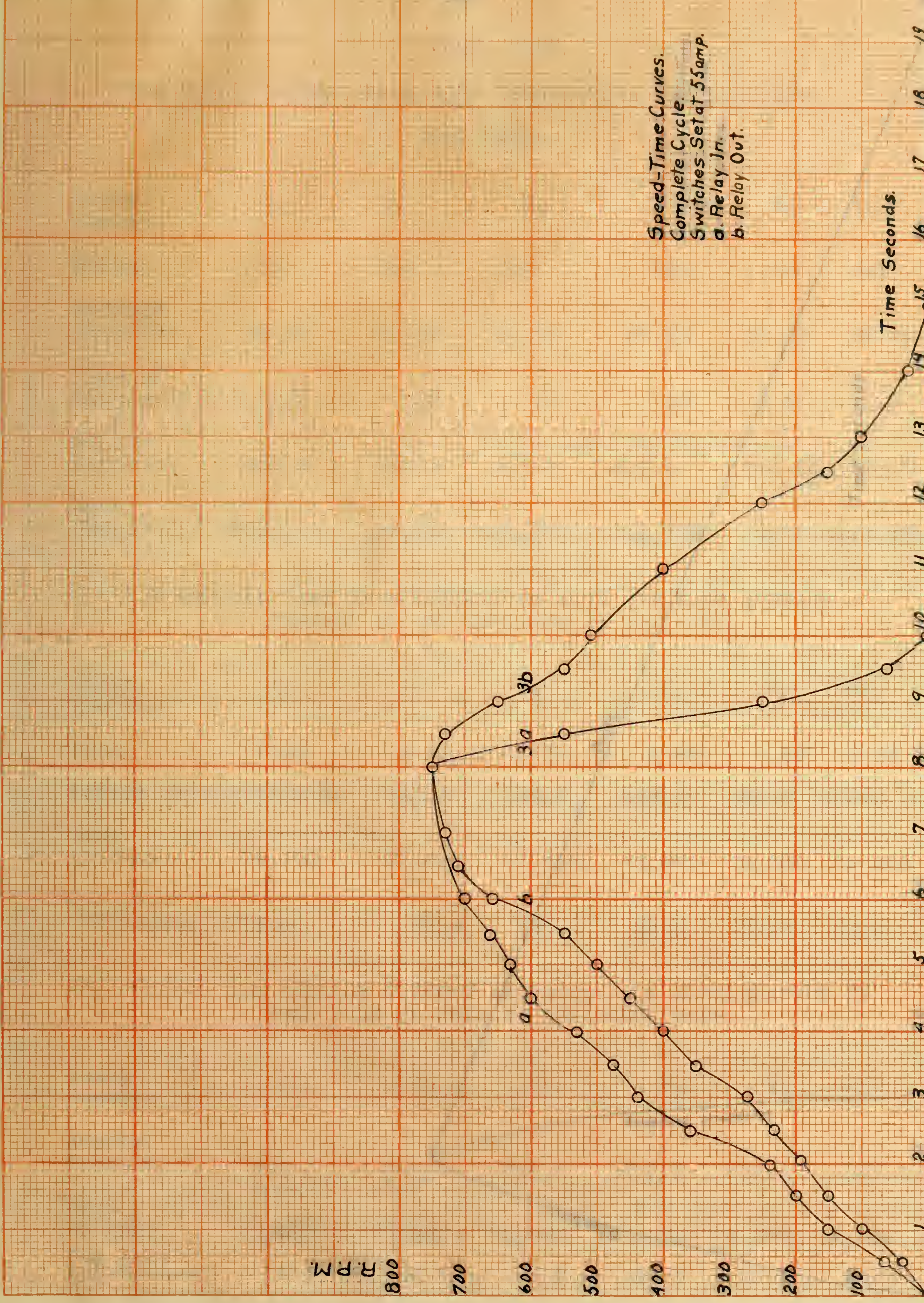

Speed-Time Curves.
Complete Cycle
Switches Set at 45 amp.
a Relay In.
b Relay Out.
R P M
Time Seconds.
2a
2b
a
b
100
200
300
400
500
600
700
800
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

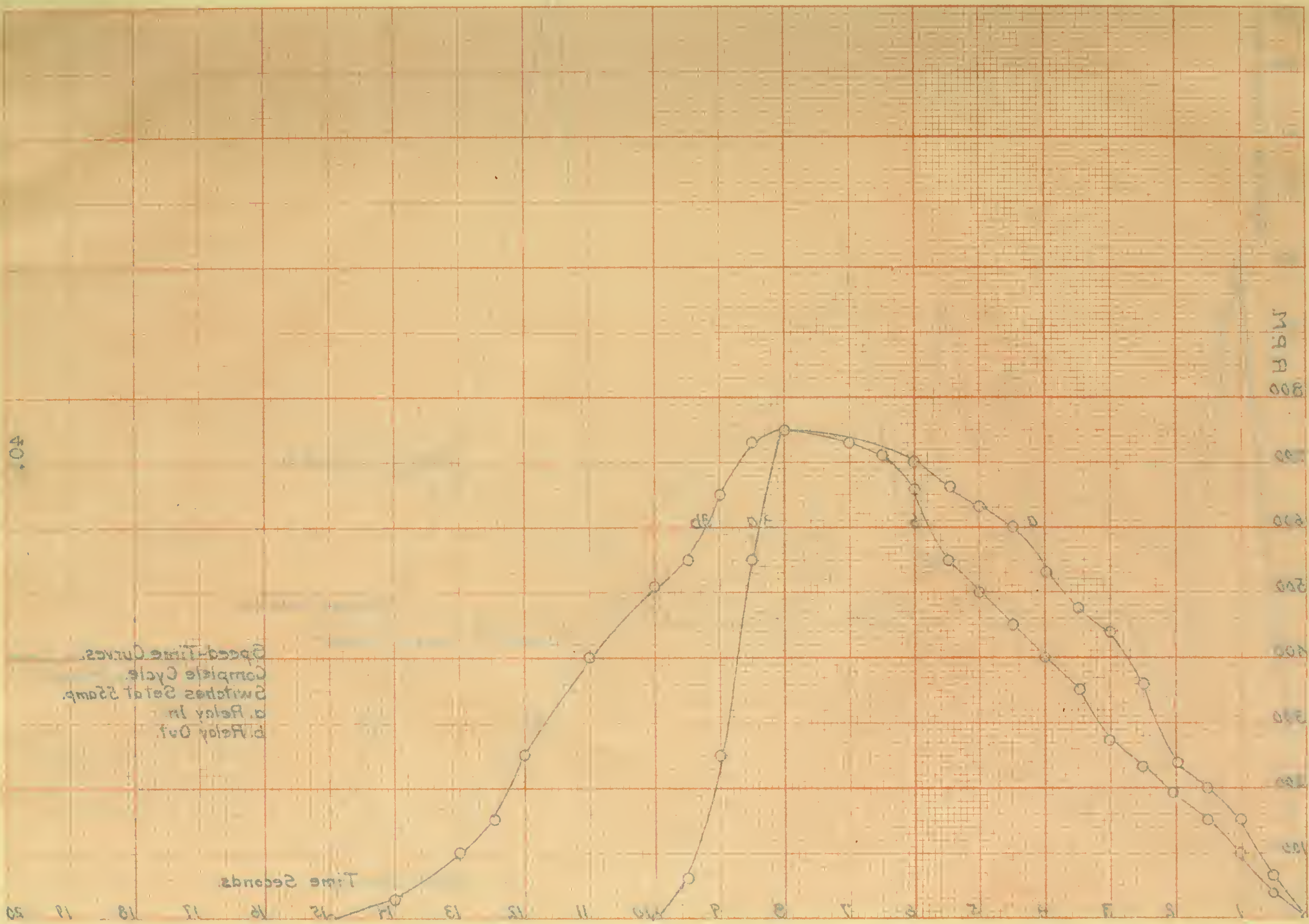

R.P.M.
800
700
600
500
400
300
200
100
1
2
3
4
5
6
7
8
9
10
Time Seconds.
3a
3b
c
d
e
Speed-Time Curves.
Switches Set at 55 amp.
a. Relay In.
b. Relay Out.
c. Theoretical Curve t = 7.5 sec.
d. Theoretical Curve. Average Current Same as for a.
e. Theoretical Curve. Average Current Same as for b.

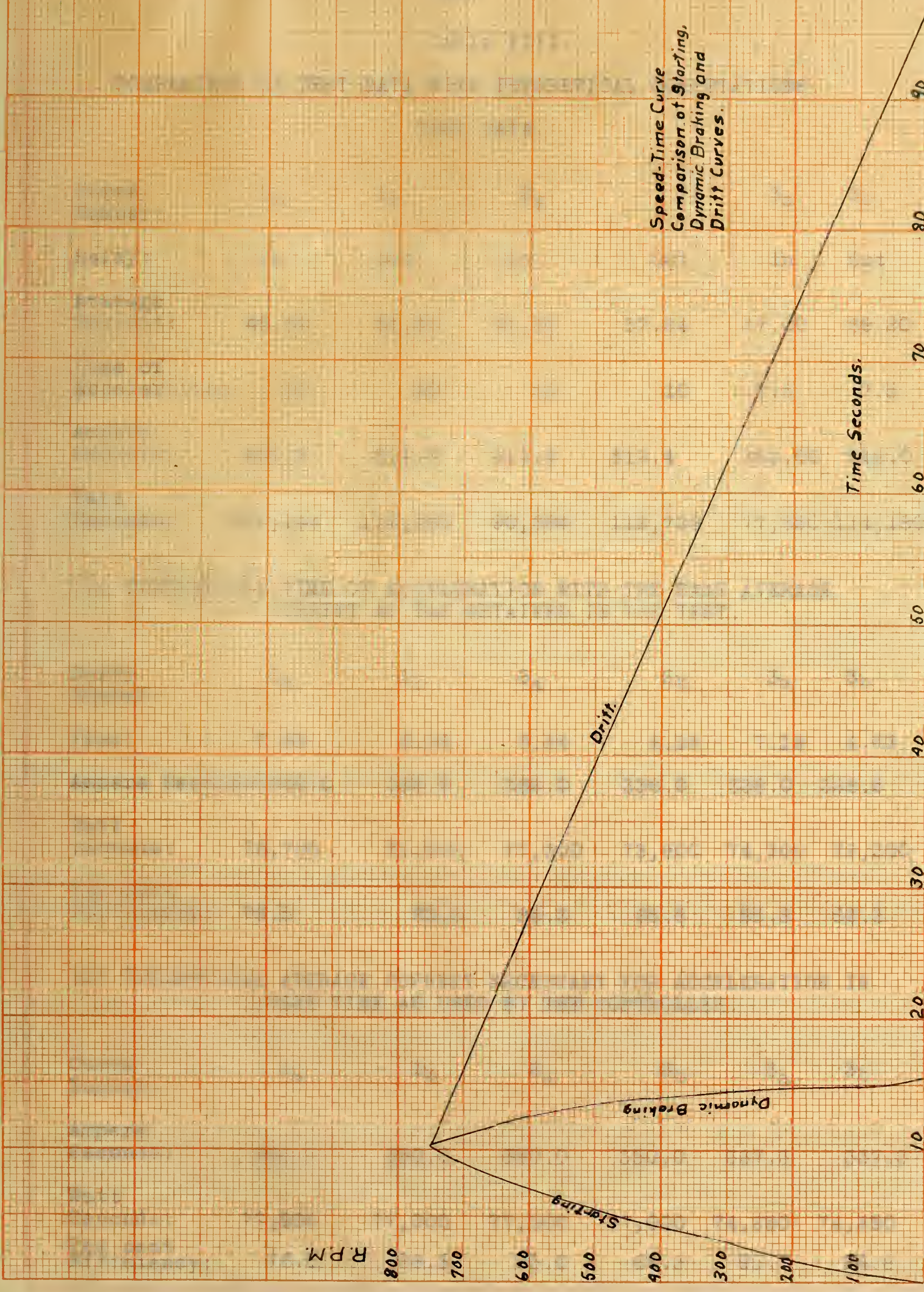

38.
Speed-Time Curves.
Switches Set at 55amp.
a. Relay In.
b. Relay Out.
c. Theoretical Curve 7.75sec
d. Theoretical Curve. Average Current Same as for a.
e. Theoretical Curve. Average Current Same as for b
Time Seconds
R.P.M.
100
200
300
400
500
600
700
800
1
2
3
4
5
6
7
8
9
3a
3b
c
d
e


Armature Current amp.
140
130
120
110
100
90
80
70
60
50
40
30
20
10
Average Current b.
Average Current a.
Theoretical Average Current.
3a
3 b.
Armature Current - Time Curves.
Switches Set at 55 amp.
a. Relay In.
b. Relay Out.
Time Seconds.
1
2
3
4
5
6
7
8
9
10


Armature Current - Time Curves
Switches Set at 55amp.
a. Relay In.
b. Relay Out.
Average Current b.
Average Current a.
Theoretical Average Current.
Time Seconds
Armature Current amp
3 b.
3 a.
30.


Speed-Time Curves.
Complete Cycle.
Switches Set at 55amp.
a. Relay In.
b. Relay Out.
Time Seconds.
R.P.M.
100
200
300
400
500
600
700
800
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
a
b
3a
3b


Speed-Time Curves.
Complete Cycle.
Switches Set at 55amp.
a. Relay In.
b. Relay Out.
Time Seconds
R.P.M.
800
700
600
500
400


Speed-Time Curve
Comparison of Starting, Dynamic Braking and Drift Curves.
Time Seconds.
10
20
30
40
50
60
70
80
90
100
R.P.M.
800
700
600
500
400
300
200
100
Drift.
Dynamic Braking
Starting

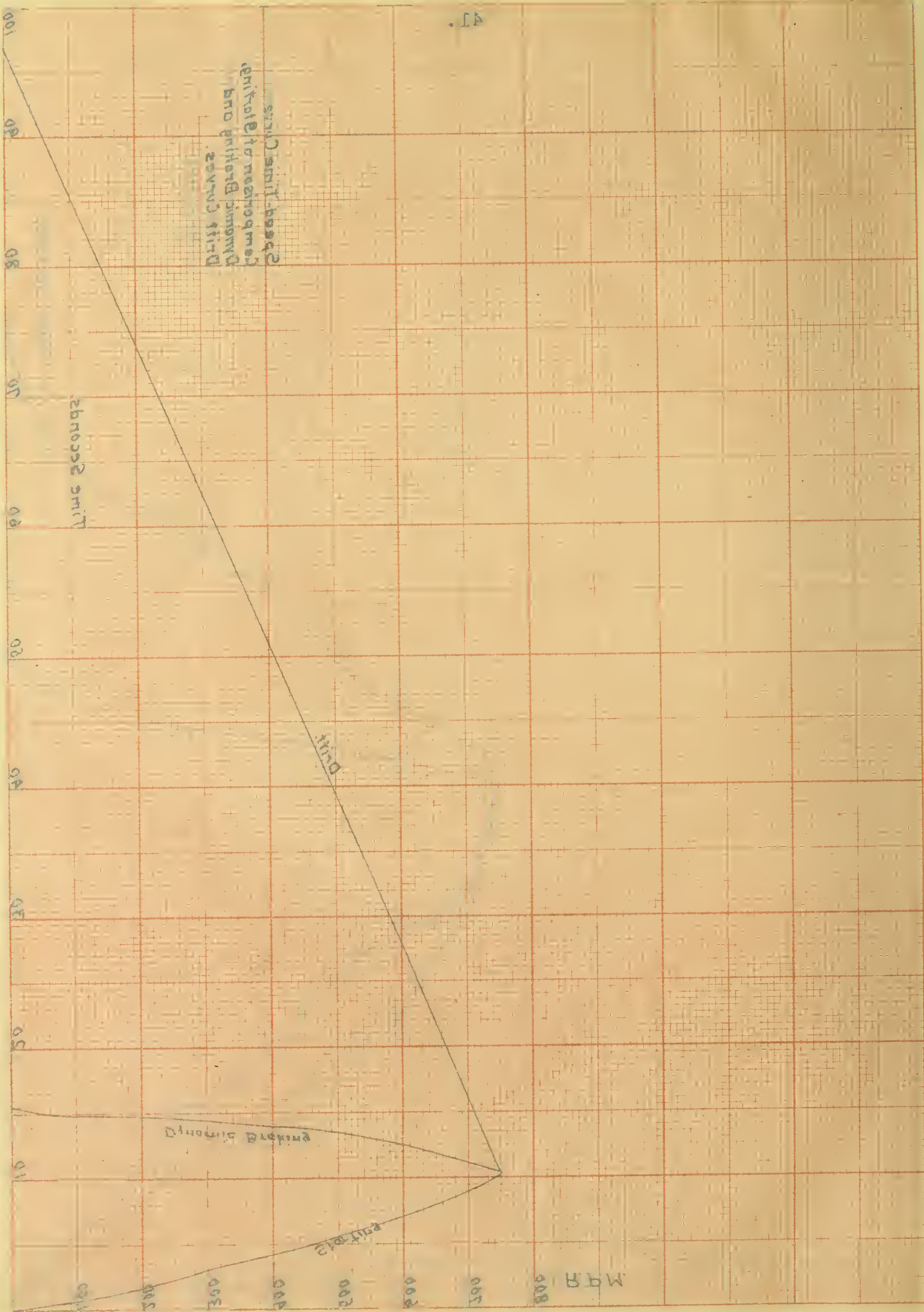

Speed-Time Curves.
Comparison of Starting,
Dynamic Braking and
Drift Curves.
Time Seconds.
R.P.M.
Drift
Starting
Dynamic Braking
100
200
300
400
500
600
700
800
10
20
30
40
50
60
70
80
90
100

Table VIII.

COMPARISON OF TEST DATA WITH THEORETICAL COMPUTATIONS.

TEST DATA.

Curve Number:	1_a	1_b	2_a	2_b	3_a	3_b
Relay:	In	Out	In	Out	In	Out
Average Current:	45.52	51.30	41.22	57.24	47.00	69.20
Time of Acceleration:	10	10	10	10	7.5	7.5
Ampere Seconds:	455.2	513.0	412.2	512.4	352.00	519.0
Watt Seconds:	100,144	112,860	90,684	112,728	77,550	114,180

(1) THEORETICAL TIME OF ACCELERATION WITH THE SAME AVERAGE CURRENT AS WAS OBTAINED IN THE TEST.

Curve Number:	1_a	1_b	2_a	2_b	3_a	3_b
Time:	7.55	6.34	8.54	6.55	7.18	4.83
Ampere Seconds:	349.0	323.5	362.0	336.0	338.0	328.5
Watt Seconds:	76,700	71,500	77,300	73,800	74,300	72,300
Per cent Efficiency:	76.5	63.5	85.3	65.6	95.8	63.3

(2) THEORETICAL AVERAGE CURRENT NECESSARY FOR ACCELERATION IN SAME TIME AS USED BY THE CONTROLLER.

Curve Number:	1_a	1_b	2_a	2_b	3_a	3_b
Ampere Seconds:	350.0	350.0	350.0	350.0	337.3	337.3
Watt Seconds:	77,000	77,000	77,000	77,000	74,250	74,250
Per cent Efficiency:	76.8	68.3	85.0	68.3	95.7	64.8

VI DISCUSSION AND CONCLUSIONS.

Upon examination of the theoretical speed-time curves on pages 32-40. it will be noted the time required to accelerate the load varied considerably with a variation of armature current and field current. In every case where the field control was used the time was much less than when the field was maintained constant. The straight line speed-time curve is characteristic of armature control when there is no change of field conditions during the time of acceleration. From a consideration of these theoretical curves it is evident that a method of starting, which embodied both armature and field control, would be very efficient.

This point by point method of obtaining the speed-time curves although quite simple in its application affords great opportunities for the study of starting conditions and should prove very important in the design of starting apparatus.

Table VIII gives in condensed form the results of the various experimental curves and also the power consumption in watt seconds for the different conditions. With the relay in, the average value of current in the three cases for different settings of the switches is about constant, while with the relay out, the average value increases with the value at which the switches were set to close. The efficiency also increases with the increase of the average value. The efficiency here is based upon the theoretical conditions.

The curves on pages 34,37,40 give the complete cycle of starting and braking. Here the effect of the field relay is quite noticeable in the time required for braking as it considerably decreases it. On page 41 is shown the complete cycle and the drifting curve plotted to scale and shows very plainly the great advantage of dynamic braking where it is necessary to start and stop or reverse frequently.

The use of the field relay did not appreciably effect the time required for acceleration as will be noted from the experimental speed-time curves on pages 32,35,38. But when the corresponding current curves on pages 33,36,39 are examined the results of the action of this relay are very evident. The peaks are not so high and the average current is considerably less. This relay is in action for only very short periods,but may close and drop out several times while the load is coming up to speed,and does not in any way perform the functions of a field control. It not only gives the motor full torque at the time when it is required but makes the starting of adjustable speed motors absolutely safe,no matter what the setting of the field rheostat may be. It allows the setting of the field rheostat to remain unchanged no matter how often the motor is to be started and stopped.

Numerous peaks are found in the current curves which are due to the starting resistance being cut out by steps instead of gradually. These peaks occur when the automatic switches close. Undoubtedly they are higher than they should be on account of the poor damping effect of the meter. The

back throw is also below the point which would allow the switch to close if the meter had been properly damped. This is plainly shown as the curve goes up rapidly after the return swing and then falls slowly off until the next switch closes.

The curve (a) of the speed-time curve on pages 32,35,38 is the one obtained with the relay in, and (b) with the relay out. Curve (c) is the theoretical curve obtained by assuming the time the same as for the actual curves (a) and (b). The curves (d) and (e) were obtained by assuming the average current the same as for the actual curves and solving for the time required to accelerate theoretically. In every case these last named curves show that the theoretical time required is less than the experimental. As the inertia of the motor was not considered in the development of the theoretical curves, and as it will affect the time of acceleration experimentally, part of the difference in time between the theoretical and actual may be ascribed to this error.

On the same pages as the current curves are shown the average values for the experimental curves and also the average current as calculated assuming the time the same as the experimental.

At no time either in starting, braking, or reversing was there any evidence that the motor was being punished as no sparking appeared at the brushes under the most severe conditions. In this connection, however, it is important to bear in mind that the motor had interpoles which afford

the best of conditions in regard to commutation.

In conclusion it is important to note that the experimental curves as obtained by the use of the automatic starter compare very favorably with the theoretical conditions in respect to average current values and time required for acceleration. The starting current is effectively limited by the use of the field relay.

This type of starter with its combined starting, braking, and reversing properties seems to have very satisfactorily solved the problem of the operation of direct current shunt motors so far as armature control is concerned. The advantage from the standpoint of safety is apparent as the ability to stop promptly adds greatly to the safety in the operation of machinery and tools.

From the theoretical considerations it seems that a type of starter might be designed combining armature and field control which would prove very efficient from the standpoint of time required for acceleration and comparatively low value of starting current.